HETEROSIS AND COMBINING ABILITY STUDIES FOR GRAIN IRON AND ZINC CONTENTS IN SORGHUM (*Sorghum bicolor* L. Moench)

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B.Sc. (Ag.)

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(GENETICS AND PLANT BREEDING)

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BY

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2012

DECLARATION

I, **V.P.L. GAYATHRI SURAVARAM**, hereby declare that the thesis entitled "**HETEROSIS AND COMBINING ABILITY STUDIES FOR GRAIN IRON AND ZINC CONTENTS IN SORGHUM (*Sorghum bicolor* L. Moench)"** submitted to the **Acharya N.G. Ranga Agricultural University** for the degree of **MASTER OF SCIENCE IN AGRICULTURE** in the major field of **GENETICS AND PLANT BREEDING** is the result of original research work done by me. I further declare that the thesis or any part thereof has not been published earlier elsewhere in any manner.

Place: Rajendranagar **(V.P.L. GAYATHRISURAVARAM)**

Date: 27-06-2012 **I.D. No. RAM/10-31**

CERTIFICATE

Ms. V.P.L. GAYATHRI SURAVARAM has satisfactorily prosecuted the course of research and that the thesis entitled **"HETEROSIS AND COMBINING ABILITY STUDIES FOR GRAIN IRON AND ZINC CONTENTS IN SORGHUM (*Sorghum bicolor* L. Moench)"** submitted is the result of original research work and is of sufficiently high standard to warrant its presentation to the examination. I also certify that neither the thesis nor its part thereof has been previously submitted by her for a degree of any University.

(K. RADHIKA)

Date: 27-06-2012 **Chairperson**

CERTIFICATE

This is to certify that the thesis entitled **"HETEROSIS AND COMBINING ABILITY STUDIES FOR GRAIN IRON AND ZINC CONTENTS IN SORGHUM (*Sorghum bicolor* L. Moench)"** submitted in partial fulfilment of the requirements for the degree of **MASTER OF SCIENCE IN AGRICULTURE (GENETICS AND PLANT BREEDING)** of the Acharya N.G. Ranga Agricultural University, Hyderabad is a record of the bonafide original research work carried out by **Ms. V.P.L. GAYATHRI SURAVARAM** under my guidance and supervision.

No part of the thesis has been submitted for any other degree or diploma. The published part and all assistance received during the course of investigation have been duly acknowledged by the author of the thesis.

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LIST OF ILLUSTRATIONS

LIST OF SYMBOLS AND ABBREVIATIONS

%	:	Per cent
ANOVA	:	Analysis of Variance
A.P.	:	Andhra Pradesh
B	:	Boron
CMIE	:	Centre
Ca	:	Calcium
C.D.	:	Critical Difference
CGIAR	:	Consultative Group on International Agricultural Research
CoV	:	Covariance
Cu	:	Copper
DC	:	Direct Cross
E	:	East
EMS	:	Error Mean Sum of Square
et al.	:	and other workers
F_1	:	First filial generation
F_2	:	Second filial generation
Fe	:	Iron
g	:	Gram
GCA	:	General Combining Ability variance
gca	:	General Combining Ability effect
ha^{-1}	:	Per hectare
ICRISAT	:	International Crops Research Institute for Semi-Arid Tropics
K	:	Potassium
kg ha^{-1}	:	Kilograms per hectare
LSD	:	Least Significant Difference
M ha	:	Million hectares
M t	:	Million tonnes
Mg	:	Magnesium
mg $100g^{-1}$	:	Milligram per 100 grams
Mn	:	Manganese

N	:	Nitrogen
No.	:	Number
P	:	Phosphorous
ppm	:	Parts per million
P_2O_5	:	Phosphorous pentoxide
r	:	Correlation coefficient
RBD		Randomized Block Design
RC	:	Reciprocal Cross
S	:	Selfing
S	:	Sulphur
SEm	:	Standard error mean
SCA	:	Specific Combining Ability variance
sca	:	Specific Combining Ability effect
viz.	:	Namely
WHO	:	World Health Organisation
XRF	:	X-Ray Flourescence
Zn	:	Zinc

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ABSTRACT

The present investigation was undertaken in grain sorghum to estimate the heterosis and to study the nature of gene action and combining ability for grain iron and zinc contents as well as to understand the correlations of grain iron and zinc contents with grain yield and other important characters and the direct and indirect effects of these traits on grain iron and zinc contents in sorghum. Two separate experiments were conducted by using parents with varied levels of grain iron in one experiment and those with diversified contents of grain zinc in another experiment.

In the first experiment, four parental lines (IS 2263, IS 13211, IS 10305 and SPV 1359) were crossed among each other in a full-diallel fashion and the resultant twelve crosses along with four parents and standard check (ICSR 40) were evaluated during two *postrainy* seasons, 2010-2011 and 2011-2012 in Randomized Block Design (RBD) with three replications. Significant variation was observed among the genotypes, environment and genotype x environment interaction for all the characters studied (plant height, days to 50 % flowering, 100-grain weight, grain yield and grain zinc) except 100-grain weight. Heterosis for grain iron varied from -9.07 % to 12.89 % over mid-parent, from -14.72 % to 8.55 % over better parent and from -7.19 % to 30.57 % over standard check across the seasons. Heterosis was found to be non-significant over mid-parent and better parent, indicating that additive gene action had a predominant role in the inheritance of this trait. Most of the hybrids recorded significant heterosis over standard check.

The combined analysis of variance for combining ability revealed significant differences among parents, direct crosses and reciprocal crosses indicating the existence of wider variability in the material under study for all the characters. However, direct crosses did not show significant variation for grain iron. The ratios of GCA/SCA variances revealed that additive gene action was predominant in the inheritance of all the characters studied barring days to 50 % flowering. Predictability ratio revealed that grain iron content was found to be governed by additive gene action. IS 2263 and IS 13211 were found to be promising general combiners for grain iron based on *gca* effects and SPV 1359 X IS 13211, IS 10305 X IS 13211, IS 10305 X

IS 2263, SPV 1359 X IS 2263 and IS 2263 X IS 13211 were identified as promising hybrids for grain iron based on *sca* effects. Correlation studies revealed that plant height showed positive correlation, while days to 50 % flowering showed negative correlation with grain iron during *postrainy* season, 2010. Plant height, 100-grain weight and grain yield showed negative correlation, while days to 50 % flowering showed positive correlation with grain iron content in 2011. This difference might be attributed to the influence of environment on these traits. Path values obtained in this study indicated that plant height, days to 50 % flowering and 100-grain weight showed controversial direct effects on grain iron in two seasons due to environmental influence. Grain yield showed negative direct effect on grain iron content consistently in both the seasons. Higher magnitude of residual effect obtained in both the seasons indicated that it might be necessary to include some more characters closely related with grain iron content.

Four parental lines contrasting for grain zinc (IS 2248, IS 20843, PVK 801 and ICSB 56) were crossed among each other in a full-diallel fashion in second experiment and the resultant twelve crosses along with their parents and standard check (ICSR 40) were evaluated during two *postrainy* seasons, 2010-2011 and 2011-2012 in Randomized Block Design (RBD) with three replications. Analysis of variance revealed that genotypes and genotype x environment interaction were significant for all the five characters studied and environment was significant for plant height, days to 50 % flowering and grain yield. Heterosis for grain zinc ranged from -28.77 % to 28.23 % over mid-parent, from -21.12 % to 37.09 % over better parent and from -21.61 % to 84.08 % over standard check across the seasons. Majority of the hybrids did not exhibit significant heterosis over mid-parent, better parent and standard check, suggesting that additive gene action governed the inheritance of this trait. Barring few crosses, none of the hybrids outperformed significantly the parents which had high level of grain zinc, indicating that there would be little opportunity, if any, to exploit heterosis for improving this trait.

The combined analysis of variance for combining ability revealed significant differences among parents, direct crosses and reciprocal crosses indicating the existence of wider variability in the material under study for all the characters in this experiment. However, reciprocal crosses did not show significant variation for plant height and grain zinc. The ratios of GCA/SCA variances revealed that non-additive gene action was predominant in controlling all the characters studied barring grain zinc. Predictability ratio revealed that grain zinc content was found to be governed by additive gene action with little role of non-additive gene action. IS 2248 and IS 20843 were found to be promising general combiners based on *gca* effects and three hybrids *viz.*, IS 2248 X IS 20843, IS 20843 X IS 2248 and IS 2248 X PVK 801 were proven to be superior for grain zinc based on *per se* performance, significant *sca* effects and heterosis over standard check. Plant height and 100-grain weight had positive correlation with grain zinc, while days to 50 % flowering showed negative association with grain zinc in both the *postrainy* seasons, 2010 and 2011. Grain yield showed positive association in 2010, while negative correlation in 2011 with grain zinc, which can be attributed to the influence of environment on these traits. Plant height showed positive direct effect, while days to 50 % flowering and grain yield showed negative direct effect on grain zinc consistently in both the seasons. Many of the characters had positive indirect effect through plant height, while negative direct effect through grain yield on grain zinc. Higher magnitude of residual effect obtained in both the seasons indicated that it might be necessary to include some more characters closely related with grain zinc content.

CHAPTER I

INTRODUCTION

Chapter I

INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench), the fifth most important cereal crop in the world after wheat, maize, rice and barley, is a major cereal staple food and forage crop of the semi-arid tropics of Indian sub-continent and several African regions. Sorghum is a staple food for about 300 million people who live in the dry tropics and temperate regions. In India, the *rainy* season sorghum grain is used mostly as animal feed while the *postrainy* season sorghum grain is primarily used for human consumption. It is the fourth most important food crop in India after rice, wheat and maize. India is one of the largest sorghum growers in the world with an area of 7.53 M ha and production of 7.25 M t with an average productivity of 963 kg ha^{-1}. In Andhra Pradesh, it covers an area of 0.28 M ha with a production of 0.44 M t with an average productivity of 1574 kg ha^{-1} (CMIE, 2009). The area under sorghum is declining in India over years which can be attributed to the low remuneration for rainy season sorghum grains because of the grain molds and change in consumer preference for food grains in favour of fine cereals such as rice and wheat. However, sorghum is a risk aversion crop, tolerant to drought and heat due to its C_4 characteristics. It is well adapted to the semi-arid and arid climatic conditions of Africa and Asia.

Sorghum cannot be excluded from cropping systems as it is a sustainable fodder source for meeting huge livestock demand under drought conditions in addition to its food value. Sorghum is good choice as a rotation crop to maintain soil fertility and to manage pests.

Sorghum is the second cheapest source of energy in the form of starch (63.4 - 72.5 %) and micronutrients such as iron (Fe) and zinc (Zn) after pearl millet. The poor and vulnerable groups in the society, particularly in India, depend upon sorghum for their calorie and micronutrient requirement in the absence of access and affordability to nutrient-rich foods like vegetables, fruits and animal products. To highlight the importance of sorghum in the human diets, there is a need to emphasize the multidisciplinary approach to evaluate the contribution of sorghum in the intake of grain Fe and Zn by poor people in the world especially in Asia and Africa (Kayode, 2006). Earlier research at ICRISAT (International Crops Research Institute for Semi-

Arid Tropics) indicated that the contribution of sorghum in iron intake was as high as 50 % in the low income group population in India (Rao *et al*., 2006).

Modern agricultural systems are adept at providing calories, but in the process, they have increased hidden hunger among the world's poor by displacing acreage allotted to traditional crops such as pulses, making many micronutrient-rich plant foods less available and more expensive to low-income families (Combs *et al*., 1996). Green revolution crops successfully increased the per capita availability of food energy but were associated with a decline in the density of dietary iron in the people of South Asia and the incidence of iron-deficiency (anaemia) that has increased in pre-menopausal women. Micronutrient malnutrition, primarily the result of diets poor in bio-available vitamins and minerals, causes blindness and anaemia (even death) in more than half of the world's population, especially among women of reproductive age, pregnant and lactating women and also pre-school children (Underwood, 2000; Sharma, 2003 and Welch and Graham, 2004) and efforts are being made to provide fortified foods to the vulnerable groups of the society. World Health Organization (WHO) of the United Nations recognized that the two micronutrients iron and zinc and pro-vitamin A (β-carotene) are limiting. Human nutritionists have focused on supplementation, fortification and dietary diversification as the three principal interventions to reduce micronutrient malnutrition. Biofortification, whereever possible, is a cost effective and sustainable solution for tackling the micronutrient deficiencies as the intake of micronutrients is on a continuing basis with no additional costs to the consumer in the developing countries (Kumar *et al*., 2011). Biofortification of sorghum by increasing mineral micronutrients, especially iron and zinc in the grains is of widespread interest (Pfeiffer and McClafferty, 2007 and Kumar *et al*., 2009).

The introduction of crop varieties selected and bred for increased iron and zinc contents through plant breeding approach will complement the existing approaches (such as fortified foods and food supplementation while processing) to combat the micronutrient deficiency. The plant breeding approach would avoid dependency on behavioural changes in farmers or consumers unlike other programs (Reddy *et al*., 2005). In order to realize the potential impact of the micronutrient-dense cultivars, the micronutrient-rich cultivars must be delivered in high-yielding backgrounds with farmer's preferred traits such as early maturity and large seed size (Kumar *et al*., 2010). However, limited information is available on the character association between grain iron and zinc contents and their associations with other agronomic traits.

Research has demonstrated that large genetic variability for micronutrients are available within the genomes of major staple crops that could allow substantial increase in grain iron and zinc content through genetic enhancement (Welch, 2001). The Consultative Group on International Agricultural Research (CGIAR) has been investigating the genetic potential to increase bioavailable iron and zinc in staple food crops including the cereal crops such as rice, wheat, maize, sorghum and pearl millet. The 'HarvestPlus' biofortification challenge program on sorghum research at ICRISAT aims at genetically enhancing the grain iron and zinc contents in agronomically superior varieties of sorghum.

Heterosis is expressed as per cent increase or decrease of F_1 hybrid performance over the mid parental value (Mutazing, 1945 and Pal and Singh, 1946). Since the better parent may fall on either extreme, depending upon the traits, heterosis may result in any one of the two directions, positive or negative. The utilization of heterosis or hybrid vigour as a means of maximizing the yield of agricultural crops has become one of the most important techniques in plant breeding. Knowledge on the magnitude of heterosis for various characters is essential to locate better combinations to exploit them through heterosis breeding. The economic heterosis, rather than mid parent heterosis and heterobeltiosis, reflects the actual superiority over the best existing cultivar to be replaced and appears to be more relevant and practical.

Combining ability analysis helps to get an insight into the inheritance through the predominance of general combining ability (GCA) over specific combining ability (SCA) variances and *vice-versa*. It helps the breeder to select the parents with good *gca* effects and crosses with good *sca* effects and the appropriate breeding methodology to achieve the objective quickly and reliably. The effects of *gca* and *sca* are important indicators of potential value for inbred lines in hybrid combinations. Differences in *gca* effects have been attributed to additive, the interaction of additive x additive and the higher-order interactions of additive genetic effects in the base population, while differences in *sca* effects have been attributed to non-additive genetic variance (Falconer, 1981). The concept of *gca* and *sca* has become increasingly important to plant breeders because of the widespread use of hybrid cultivars in many crops (Wilson *et al.*, 1978).

Diallel mating system suggested by Griffing (1956) aids in the estimation of the combining ability effects and consequently helps in the identification of superior parents and single cross hybrids. It provides good information on the genetic identity of genotypes especially on dominance-recessive relations and some other genetic interactions. Diallel crosses have been used in genetic research to determine the inheritance of a trait among a set of genotypes and to identify superior parents for hybrid or cultivar development.

The estimates of correlation co-efficients among the different characters indicate the extent of direct association. The correlation co-efficient provides a reliable measure of association among the characters and helps to differentiate vital associations useful in breeding from those of the non-vital ones (Falconer, 1981). The study of relationships among quantitative traits is important for assessing the feasibility of joint selection of two or more traits and hence for evaluating the effect of selection for secondary traits on genetic gain for the primary trait under consideration. A positive genetic correlation between two desirable traits makes the job of the plant breeder easy for improving both the traits simultaneously. On the other hand, a negative correlation between two desirable traits impedes or makes it impossible to achieve a significant and simultaneous improvement in both traits.

Path analysis partitions the total correlation coefficient into direct and indirect effects and measures the relative importance of the causal factor individually (Dewey and Lu, 1959). The major advantage of path analysis is that, it permits the partitioning of the correlation coefficient into its components. It helps in assessing the cause-effect relationship as well as effective selection. The estimates of correlation and path coefficients can help us to understand the roles and relative contributions of various plant traits in establishing the growth behaviour of crop cultivars under given environmental conditions (Akhtar *et al.*, 2007). Keeping all these points in view, the present investigation was undertaken in sorghum in collaboration with ICRISAT with the following objectives:

Objectives of Investigation:

1) To study the extent of heterosis for grain iron and zinc contents in sorghum.
2) To study the general combining ability (*gca*) and specific combining ability (*sca*) effects for grain iron and zinc contents in sorghum.
3) To study the character associations of grain iron and zinc contents with other agronomic traits.
4) To estimate the direct and indirect effects of various agronomic characters on grain iron and zinc contents in sorghum.

CHAPTER II

REVIEW OF LITERATURE

Chapter-II

REVIEW OF LITERATURE

Sorghum [*Sorghum bicolor* (L.) Moench] is an important food and feed crop in the semi-arid regions of the world where it is grown under rain fed and irrigated conditions Sorghum is considered as a nutritious cereal crop in providing high quality both for human and animal consumption that will continue to play an important role in Indian economy. However, genetic investigations on the grain iron and zinc content of grain sorghum have been comparatively limited. The exploitation of heterosis by developing the hybrids is one of the quickest and simpler ways to improve the grain iron and zinc content of sorghum. Before placing strong emphasis on breeding for nutritional quality characters (grain iron and zinc), the knowledge on the association between yield and its attributes and also interrelationship between yield and nutritional quality characters will enable the breeder for simultaneous improvement of yield with nutritional traits. The correlation coefficient may help to identify characters that have little or no importance in the selection programme. The most appropriate breeding methodology to be adopted for improvement of any crop depends primarily on the combining ability of the parents in the hybridization programme and also the nature of gene action involved in the expression of quantitative traits of economic importance. Diallel analysis is the precise method for obtaining such information. The investigations made on heterosis, combining ability, character associations and direct and indirect effects of agronomic traits on grain iron and zinc has been very useful in further improvement programmes. A brief review of literature available on above aspects in grain sorghum is presented in this section, under the following sub-headings.

- Variability and heritability
- Heterosis
- Combining ability analysis
- Correlation studies
- Path co-efficient analysis

2.1 Variability and Heritability

Phenotypic variability expressed by a genotype or a group of genotypes in any species can be partitioned into genotypic and phenotypic components. The genotypic component being the heritable part of the total variability, its magnitude on yield and its component characters influences the selection strategies to be adopted by the breeder. Heritability in broad sense is the ratio between the genotypic variance as a whole that is due to phenotype. The genetic gain that can be expected for a particular character through selection is the product of its heritability, phenotypic standard deviation and selection differential. Heritability estimates along with genetic gain are considered to be more useful in predicting the outcome of selecting the best individuals (Johanson *et al*., 1955).

Amirthadevarathinam and Sankarapandian (1994) reported high genetic advance coupled with high heritability for plant yield and 100 seed weight and high heritability coupled with low genetic advance for plant height and leaf area suggesting the operation of non-additive gene action and further found positive and significant correlation between plant yield and 100 seed weight in sorghum.

Maloo *et al.* (1998) reported high potential genetic gain along with high estimates of GCA and broadsense heritability for quality traits like seed iron content in finger millet, indicating that this trait is largely governed by additive gene effects that in turn could be improved by selection.

Can and Yoshida (1999) obtained large proportion of phenotypic variance, which was attributable to the genotypic variance for plant height, 100 grain weight and grain yield in sorghum.

Brkic *et al*. (2003) estimated the grain iron content in the range of 13.6-30.3 mg kg^{-1} and grain zinc content in the range of 16.0-23.6 mg kg^{-1} in maize and suggested the possibility to improve several minerals simultaneously due to no negative and significantly positive associations among minerals.

Kayode *et al*. (2006) determined that the iron concentration of the sorghum grains ranged from 30 to 113 mg kg^{-1} with an average of 58 mg kg^{-1} and the zinc concentration ranged from 11 to 44 mg kg^{-1} with an average of 25 mg kg^{-1}.

Oury *et al*. (2006) estimated iron and zinc concentrations in the range of 20 to 60 ppm and 15 to 35 ppm, respectively in sorghum.

Reddy *et al*. (2006) reported considerable genetic variability coupled with high broad-sense heritability, suggesting good prospects of genetic enhancement for grain iron and zinc density through conventional breeding complemented by molecular breeding.

Hemalatha *et al.* (2007) estimated the variability in zinc content ranged from 1.08 mg 100 g^{-1} in rice to 2.24 mg 100 g^{-1} in sorghum and iron content ranged from 3.85 mg 100 g^{-1} in rice to 6.51 mg 100 g^{-1} in sorghum.

Ling and Kaun (2010) showed that the distribution of mineral element contents in the F_2 populations exceeded the performances of their parents, indicating the possibility for selecting the offspring with abundant of mineral nutrients from the F_2 populations in rice.

Nguni *et al.* (2011) reported that farmer varieties of sorghum showed superiority for grain Fe content ranging from 2.74 to 8.18 mg 100 g^{-1} and grain zinc content ranging from 2.03 to 5.53 mg 100 g^{-1}.

2.2 Heterosis

An increase in vigour due to crossing two homozygous inbred lines and decrease in vigour due to inbreeding are manifestations of the same phenomenon *i.e.,* heterozygosis. The heterosis can be defined in terms of superiority of F_1 hybrid over better parent. Since the better parent may fall on either extreme, depending upon the traits, heterosis may infest in any one of the two directions, positive and negative.

The utilization of heterosis or hybrid vigour as a means of maximizing the yield of agricultural crops has become one of the most important techniques in plant breeding. In sorghum, heterosis was described and defined in the literature ever before hybrid sorghum became especially important and the first report of heterosis in the crop was given by Conner and Karper (1927). Karper and Quinby (1937) found that *milo* and *hegari* hybrids invariably possessed extreme vigour and these cultivars apparently possess many dominant alleles favourable for growth and production. The occurrence of cytoplasmic genetic male sterility led to the development of hybrids on commercial scale. In India, the first two hybrids CSH1 and CSH2 were released in 1964 and 1965 which made the beginning of sorghum hybrid era by Rao (1972).

In sorghum, heterosis for different traits has been reported and commercially utilized by number of workers, the details of which are presented here under.

Kirby and Atkins (1968) found that significant average heterosis was expressed by the sorghum hybrids for grain yield and plant height and also observed greatest heterotic response for grain yield, where hybrids averaged 122 % of the mid-parent values, with a range of 106 to 147 % among individual hybrids.

Rao and Goud (1977) concluded that the overdominance conditioned the grain yield in sorghum. They further observed maximum heterosis for grain yield in IS 2226 (dwarf introduction) X Karad Local (tall), resulting from additive X additive gene interaction.

Giriraj (1983) reported that heterosis for grain yield was mainly due to the heterotic effect expressed for 100-grain weight in sorghum which was not related to genetic divergence.

Nandanwankar (1990) concluded that sorghum hybrids showing significant heterobeltiosis for grain yield were also significantly superior for atleast 3 to 4 ear and grain characters and they further reported that heterosis for grain yield was due to increased number of seeds/ear head, secondaries and ear weight.

Badhe and Patil (1997) found that the most of the heterotic combinations in sorghum were between geographically diverse parents and these were heterotic for all the panicle characters and plant height.

Rajguru *et al*. (2005a) identified the sorghum cross combinations 116A X RS-29, 3642A X SPV-489, 53A X SPV-1277 and 36642A X RSE-5 with the highest magnitude of heterosis for grain yield and its components.

Rajguru *et al*. (2005b) concluded that the *per se* performance of cytoplasmic genetic male sterile lines, restorer lines and their hybrids was related to heterotic effects in *rabi* sorghum.

Chaudhary *et al*. (2006) evaluated seven sorghum hybrids for their performance in *rabi* season and showed significant useful heterosis for grain yield and other yield contributing characters.

Desai *et al*. (2006) showed significant heterosis for all the yield components except panicle length in sorghum and further concluded that the crosses that exhibited heterobeltiosis showed higher grain size.

Iyanar and Gopalan (2006) found close association between *per se* performance of hybrids and heterosis for all the agronomic traits except for leaf number and seed yield, suggesting that the selection of the crosses based on *per se* performance could be more realistic in sorghum.

Jayalakshmi *et al*. (2006) identified three promising hybrids, *i.e*. NTJ 3 × CSV 13, NTJ 4 × NJ 2575 and NJT 4 × SPV 1532, with desirable heterobeltiosis for grain yield and panicle weight, which could be used for further exploitation in sorghum breeding programs.

Chen *et al*. (2007) showed that heterosis of iron concentration was very low, indicating that traditional hybrid breeding may not be efficient for improving this trait by analysing nine maize inbred lines.

Ghorade and Ghive (2007) reported highest heterobeltiosis (38.43 %) in respect of grain yield, plant height, days to 50 % flowering and all panicle characters in the sorghum cross ms-104A X AKR-354.

Khapre *et al*. (2007) concluded that the crosses SPV 1422 × SPV 1359, SPV 1500 × PVR 524, SPV 1502 × PVR 524, SPV 1422 × SPV 1413 and SPV 1500 × RR 9808 exhibited significantly high heterobeltiosis and standard heterosis over M 35-1, CSH 15 R and SPV 655 in sorghum.

Kulkarni *et al*. (2007) reported pronounced hybrid vigour for grain yield, panicle length, panicle breadth, 1000-seed weight and fodder yield, while it was low for earliness, *i.e*. days to 50 % flowering in sorghum.

Vragolovic *et al*. (2007) noticed that heterosis was not significant for leaf and grain Fe and Zn concentrations in maize. They further found that the Fe and Zn concentrations varied from 15.9 to 24.8 mg kg^{-1} and 19.2 to 24.1 mg kg^{-1}, respectively.

Wadikar *et al*. (2007) identified the cross PMS 37 A × RS 29 with greatest significant heterotic effects for grain yield per plant at both physiological and normal maturity in sorghum.

Rani and Rao (2009) found that there was no perfect correspondence between level of heterosis expressed in a cross and genetic divergence between parents in grain sorghum.

Makanda *et al*. (2010) found that the overall hybrid mean yield was significantly higher than that of parents and standard check varieties, which was attributed to high levels of average heterosis and standard heterosis, respectively in sorghum.

Showemimo *et al*. (2010) observed high heterotic value of 692.03 % for grain yield in sorghum and concluded that the hybrids that exhibited high heterotic value for grain yield also has high heterotic value for yield components *viz*., 1000 seed weight and number of seed per panicle.

Sajjanar *et al*. (2011) reported that the crosses, Atharga Kempu Jola × M 35-1 showed high level of significant positive heterosis for panicle weight (79.8 and

73.2 % over midparent and better parent/control, respectively) and grain yield (109.7 and 99.5 % over midparent and better parent/control, respectively).

Velu *et al*. (2011) found that hybrids did not outperform the parents having high Fe and Zn levels, which showed that there would be little opportunity, if any, to exploit heterosis for these mineral micronutrients in pearl millet.

In addition to the above studies, a brief review on heterosis for various traits in sorghum reported by several workers is presented hereunder:

Table 2.1. Heterosis for various characters in sorghum

Character	Heterosis	References
Plant height	Positive heterosis over mid parent	Shivanna and Patil (1988) Belavatagi (1997)
	Significant heterosis over mid parent	Kanaka (1979)
	Non-significant heterosis over mid parental values.	Giriraj and Goud (1981)
	Significant negative heterosis over mid parent	Patil and Biaradar (2005)
	Positive heterosis over better parent	Senthil and Palaniswamy (1993) Ganesh *et al.* (1996) Lokapur (1997) Pawar (2000)
	Negative heterosis over better Parent	Naik *et al.* (1994) Madhusudana and Patil (1996) Lokapur (1997) Pawar (2000)

Table 2.1. (contd.)

Character	Heterosis	References
Plant height	Heterosis over standard check	Shivanna and Patil (1988)
	Significant heterosis over commercial check	Patel *et al.* (1987) Desai (1991) Belavatagi (1997)
	Positive as well as negative Heterosis	Shivanna (1989)
Days to 50 % flowering	Heterosis over mid parent	Shivanna and Patil (1988) Belavatagi (1997)
	Positive heterosis over better parent	Senthil and Palaniswamy (1993) Pandit (1989)
	Negative heterosis	Naik *et al.* (1994) Lokapur (1997) Pawar (2000)
100-grain weight	Significant positive heterosis over mid-parent	Dinakar (1985) Sahib and Reddy (1986) Chinna and Phul (1988) Geeta and Rana (1988) Nandanwankar (1990) Patel *et al*. (1990) Senthil and Palaniswamy (1993) Sankarpandian *et al.* (1994) Lokapur (1997) Pawar (2000) Nimbalkar *et al.* (1988) Biradar (1995)

Table 2.1. (contd.)

Character	Heterosis	References
100-grain weight	Highly significant heterosis over mid-parent and better parent	Geeta and Rana (1988) Shivanna (1989) Senthil and Palaniswamy (1993) Biradar (1995) Chen (1994)
	Negative heterosis over mid-parent	Pandit (1989)
	Negative heterosis over better parent	Desai *et al.* (1985)
	Significant heterosis over mid parent, better parent and check.	Ganesh *et al.* (1996)
	Wide range of heterosis	Kanaka (1979) Desai *et al.* (1980) Shinde *et al.* (1983) Giriraj (1983) Dinakar (1985) Giriraj and Goud (1985) Shivanna and Patil (1988)
	Limited heterosis	Shivanna (1989) Rao *et al.* (1993) Biradar (1995)
Grain yield	Positive heterosis over mid parent	Nimbalkar *et al.* (1988) Wenzel (1988) Berenji (1988) Kasenko (1988) Chinna and Phul (1988)

Table 2.1. (contd.)

Character	Heterosis	References
Grain yield	Positive heterosis over mid parent	Jeebaraj *et al.* (1988) Shivanna and Patil (1988) Nandanwankar (1990) Choudhari (1992) Gururaj Rao *et al.* (1993) Sankarapandian *et al.* (1994) Ganesh *et al.* (1996)

A brief review on heterosis for grain iron and zinc reported by several workers in different crops is presented hereunder:

Table 2.2. Heterosis for grain iron and zinc contents in various crops

Character	Crop	Heterosis	References
Grain iron	Pearl millet	Significant positive heterosis over mid-parent	Aruselvi *et al.* (2006) Velu (2006) Velu *et al.* (2011)
	Maize	Significant positive heterosis over standard check	Chakraborti *et al.* (2009)
Grain zinc	Pearl millet	Significant positive heterosis over mid-parent	Aruselvi *et al.* (2006) Velu (2006) Velu *et al.* (2011)
	Maize	Significant positive heterosis over standard check	Chakraborti *et al.* (2009)

2.3 Combining Ability Analysis

The estimates of combining ability effects are especially useful to predict the relative performance of different lines in hybrid combinations. The information on the nature and magnitude of gene action is important in understanding the genetic potential of a population and to decide the breeding procedure to be adopted in a given population. The diallel analysis is a precise approach for obtaining such information. Very limited information is available on the inheritance of grain iron and zinc contents in crops.

Sprague and Tatum (1942) proposed the concepts of combining ability as a measure of gene action. They defined the term "general combining ability" (*gca*) as the average performance of a line in hybrid combinations and the term "specific combining ability" (*sca*) is used to designate the cross in which certain combinations do relatively better or worse than would be expected on the basis of average performance of a lines crossed. They further revealed that genetically *gca* is due to additive effects of genes which is fixable and *sca* is due to non-additive gene effects.

Griffing (1956) stated that *gca* was associated with genes which were additive in their effects, while *sca* was attributed primarily due to development of the additive gene effects, caused by dominance and epistasis. Further it was suggested that *gca* would include both additive as well as additive X additive interactions.

A schematic study of *gca* and *sca* of quantitative characters influencing grain iron and zinc is helpful in selecting the parents for crossing to exploit hybrid vigour (heterosis) and to isolate desirable homozygotes from segregating populations. In sorghum, Kramer (1960) was the first to report the importance of both *gca* and *sca* in the expression of yield. According to him, the additive effects were more important for *gca* and dominance and epistatic effects were important for *sca*.

Li and Chang (1970) found that much of the genetic variation for seeding-to-heading period, plant height, number of panicles per plant, panicle length, panicle weight and number of spikelets per panicle of rice was due to additive effect. They further concluded that the dominance effect was of a significant source in all the traits and indirect evidence indicated that gene interaction played a negligible role.

Arnold and Bauman (1976) detected significant variation among *gca* effects for concentrations and phosphorus, magnesium, iron, zinc, oil and protein constituents in maize grain. They found that both general and specific combining ability effects were significant for grain weight, volume and density.

Wilson *et al*. (1978) identified equal frequency of alleles with positive and negative effects for yield in sorghum. They further observed significant *gca* and *sca* effects for all traits with the latter being more important.

Khotyleva *et al*. (1980) found that overdominance was most important in the genetical control of grain yield, while dominance and nonallelic interaction were most important in controlling plant height in sorghum.

Kanaka (1982) reported that additive gene action was predominant for plant height, both additive and non-additive effects were important for days to 50 % flowering and panicle length and non-additive effects were predominant in controlling the remaining characters.

Khotyleva and Neshina (1983) found that the SCA variances for growth duration in almost all lines of sorghum exceeded the corresponding GCA variances, indicating predominance of dominance and epistasis effects in the control of the emergence-flowering period.

Patil and Thombre (1984) observed that non-additive gene effects were more important than additive effects for all the characters studied in sorghum. They further concluded that *sca* effects were more stable than *gca* effects which were attributed to additive X additive interactions.

Rafiq and Rehman (1985) analysed grain yield/plant and other yield related traits from a half-diallel cross, involving two foreign and two local lines of sorghum which gave high heritability estimates for plant height, number of days to anthesis and panicle length.

Biradar and Borikar (1985) found the additive gene effects were important for grain yield and concluded that epistatic components were important for this trait, which leads to exploitation of hybrid vigour due to the involvement of both additive and non-additive components in sorghum.

Luthra *et al*. (1986) observed that the forage sorghum varieties and hybrids had similar mineral compositions, but grain varieties had lower concentrations of Fe (39 ppm) and Zn (17 ppm) than grain hybrids and forage varieties (70 and 73 ppm of iron and 23 and 25 ppm of zinc, respectively).

Veerabadhiran *et al*. (1994) found significant differences among the genotypes for days to 50 % flowering and grain yield/plant and further reported that the days to 50 % flowering is largely under the control of non-additive gene effects as reflected by high SCA variance in sorghum.

Wei *et al*. (1996) reported that the SCA variance was larger than GCA variance for Fe content, indicating the predominance of non-additive gene effects in controlling the inheritance of Fe content in rice.

Gregorio *et al.* (2000) showed highly significant differences among the crosses and between the parents and F_1 progeny which indicates clearly a genetic effect on grain iron concentration of rice. They further revealed the presence of additive gene action (fixable genes) in addition to a significant non-additive genetic variance (non-fixable genes or unpredictable genes).

Umakanth *et al.* (2002) observed higher SCA variances than the GCA variances for grain yield and its contributing characters in sorghum, indicating the predominance of non-additive gene action in the inheritance of these characters.

Gregorio and Htut (2003) concluded that the rice cultivars with a positive *gca* effect for most of the grain mineral densities were the micronutrient-dense parents. They further showed a differential *sca* effect of crosses across mineral elements, grain Fe, Zn, Mg, P, K and S.

Kabdal *et al*. (2003) showed that GCA variances for all the panicle characters were higher than SCA variances in maize except for ear height indicating the importance of additive genes in controlling these traits.

Long *et al*. (2004) found that the *gca* effects for flour Fe and Zn concentration were significantly more important than *sca* effects in high yielding environments, indicating that *per se* line evaluation could identify promising lines in white grained-maize.

Zhang *et al*. (2004) found that the seed, maternal as well as cytoplasmic genetic effects controlled the contents of mineral elements in rice and among them, the seed genetic effects were found to be more influential than the maternal genetic effects on Fe, Zn and Mn contents. They further observed the existence of genetic correlations of seed additive, seed dominance, cytoplasm, maternal additive and maternal dominance between grain characteristics such as 100-grain weight, grain length, grain width, grain shape and mineral elements Fe, Zn, Mn and P contents.

Abo-Elwafa *et al* (2005) identified the female lines of sorghum ICSA-20 and ICSA-89002 with significantly negative and positive *gca* effects for days to 50 % flowering and grain yield per plant, respectively, which indicates that these lines had desirable gene action and could be considered as good combiners for both traits.

Sharma *et al*. (2005) showed highly significant GCA and SCA variances for grain yield plant^{-1} indicating the involvement of both additive and non-additive gene actions.

Sumathi *et al*. (2005) identified non-additive gene action as the major cause of significant variation among crosses for the grain yield and its components, which is supported by the higher magnitude of variances due to SCA than those due to GCA in finger millet.

Umakanth and Kuriakose (2005) reported that the non-additive gene action was predominant in the inheritance of all the yield components except number of primaries per panicle in sorghum.

Narain *et al*. (2007) found the inadequacy of simple additive-dominance model which reflected the presence of epistatic interaction. They further suggested that the reciprocal recurrent selection and biparental mating in early segregating generations could prove to be an effective approach for development of high yielding sorghum varieties.

Ojo *et al*. (2007) identified that GCA and SCA mean squares were not significantly different for the yield components of maize and GCA mean squares were highly significant for grain yield, indicating that additive gene action was more important than non-additive gene action for grain yield.

Solanki *et al.* (2007) observed that the GCA variances were higher than the SCA variances for all the yield components, indicating the presence of additive gene action for these traits.

Arulselvi *et al*. (2009) reported that the non-additive gene action was found to be significant in the expression of all the grain quality characters and yield in pearl millet. They further found that none of the parents as well as hybrids was found to be significant for all grain quality characters and grain yield.

Godbharle *et al*. (2010) observed that genotypic variance was lower than phenotypic variance for characters panicle length, primary branches per panicle, grains per primary branches, harvest index, grain yield and plant height of sorghum indicating that additive gene effects were operating in controlling these characters.

Prabhakar and Raut (2010) identified that SLR-13, SLR-24 and SLR-30 as good general combiner male parents for grain yield and SL-12B and SLR-10 and SLR-27 as good general combiner female parents for earliness in sorghum.

Punitha *et al*. (2010) found that non-additive gene action was predominant in majority of the characters in sweet sorghum. They identified the parents ICSA 11, ICSA 297, VMS 98001 and VMS 98002 as good general combiners for grain yield and many of the desirable attributes and the crosses *viz.*, ICSA 297 × VMS 98002, ICSA 293 × IS 14549 and ICSA 293 × ASSV 9402 as potential crosses, which had both the parents or any one of the parents with significant *gca* effects.

Bidhendi *et al*. (2011) found that *gca* and *sca* effects were significant for grain yield, number of kernel rows per ear, kernel number per row and thousand-kernel weight in maize.

Mahdy *et al*. (2011) reported that the GCA variance components as estimated from male and/or female overall environments were larger than those of SCA for days to 50 % blooming, plant height and 1000-grain weight, while, opposite results were obtained for grain yield ha^{-1} in sorghum.

Pawar *et al*. (2011) found significant values for GCA and SCA variances for all the agronomic traits except panicle girth in sorghum, indicating the importance of both additive and non-additive genetic components. They further observed preponderance of additive genetic action for days to 50 % flowering and plant height where as that of non-additive gene action for panicle weight and grain yield/plant.

Upadhyaya *et al*. (2011) observed substantial genetic variability for grain iron, zinc, calcium and protein contents in finger millet. They further found that the accessions rich in Zn content had significantly higher grain yield potential than those rich in Fe and protein content.

In addition to the above studies, a brief review on gene action for various agronomic characters reported by several workers in sorghum is presented hereunder:

Table 2.3. Gene action for different characters in sorghum

Character	Nature of gene action	Reference
Plant height	Non-additive	Hugar *et al.* (1984) Jagadishwar and Shinde (1992) Naik *et al.* (1994) Belavatagi (1997) Siddiqui and Baig (2001)
	Additive	Borikar and Bhale (1982) Sankarapandian *et al.* (1996) Nayakar (1985) Chandrashekharappa (1987) Shivanna and Patil (1988) Sakhare *et al.* (1992) Shivanna *et al.* (1992) Senthil and Palaniswamy (1994) Shivanna (1989) Chinna and Phul (1988) Iyanar *et al.* (2001)
	Additive and non-additive	Rao and Goud (1977) Giriraj and Goud (1983) Dabholkar and Lal (1987) Dinakar (1985) Chand (1996) Biradar (1995)

Table 2.3. (contd.)

Character	Nature of gene action	Reference
Days to 50 % flowering	Non-additive	Biradar (1995) Kanawade *et al.* (2001)
	Additive	Nayakar (1985) Dabholkar and Usha (1988) Shivanna *et al.* (1992) Senthil and Palaniswamy (1994) Siddiqui and Baig (2001)
	Additive and non-additive	Kanaka (1979) Patel *et al.* (1995)
100-grain weight	Non-additive	Patil and Thombre (1984) Shivanna (1989) Patel *et al*. (1990) Senthil and Palaniswamy (1994) Siddiqui and Baig (2001)
	Additive	Nayakar (1985) Dabholkar and Usha (1988) Jagadishwar and Shinde (1992) Shivanna *et al*. (1992)
Grain yield	Non-additive	Rao and Goud (1977) Wilson *et al*. (1978) Kishan and Borikar (1988) Armugam *et al*. (1995) Siddiqui and Baig (2001) Patil and Thombre (1984) Shivanna (1989)
	Additive	Iyanar *et al.* (2001) Palaniswamy and Subramanian (1986) Dinakar (1985) Senthil and Palaniswamy (1994)

A brief review on gene action for grain iron and zinc contents reported by several workers in various crops is presented hereunder:

Table 2.4. Gene action for grain iron and zinc contents in various crops

Character	Nature of gene action	Crop	Reference
Grain iron	Non-additive	Rice	Zhang *et al.* (1996)
		Pearl millet	Aruselvi *et al.* (2006)
	Additive	Pearl millet	Velu (2006) Rai *et al.* (2007) Velu *et al*. (2011)
		Maize	Arnold and Bauman (1976) Long *et al*. (2004) Chen *et al*. (2007) Chakraborti *et al*. (2009)
		Rice	Zhang *et al.* (2000) Gregorio *et al.* (2000) Gregorio (2002) Gregorio and Htut (2003)
Grain zinc	Non-additive	Rice	Zhang *et al.* (1996)
		Pearl millet	Aruselvi *et al.* (2009)
	Additive	Maize	Gorsline *et al.* (1964) Arnold and Bauman (1976) Long *et al*. (2004) Chen *et al*. (2007) Chakraborti *et al*. (2009)
		Pearl millet	Velu (2006) Rai *et al.* (2007) Velu *et al*. (2011)
	Non-additive and additive	Rice	Majumdar *et al.* (1990)

2.4 Correlation Studies

The correlation coefficient, that indicates association between two characters, is useful as a basis for selecting desirable plant type. It enables to identify character or combination of characters which might be useful as indicator of high yield with high nutritional quality. Correlation studies provide information on the association of grain iron, zinc and other agronomic characters which in turn help in the selection of high yielding genotypes with high grain iron and zinc.

Reddy *et al*. (2005) reported significant and positive correlation between The correlation coefficient, that indicates association between two characters, is useful as a basis for selecting desirable plant type. It enables to identify character or combination of characters which might be useful as indicator of high yield with high nutritional quality. Correlation studies provide information on the association of grain iron, zinc and with other agronomic characters which in turn help in the selection of genotypes with high grain iron and zinc.

Rao *et al.* (1979) found the association between days to maturity and zinc contents in sorghum and further concluded that the sorghum grain had a better balance of mineral composition as was evidenced by higher values of Ca, Mg, P and Fe than rice and maize.

Srihari and Nagur (1980) reported that grain yield of sorghum was significantly associated with 1000-grain weight and plant height.

Vogel (1989) found that grain iron and days to 50 % flowering were positively correlated, while grain iron and grain yield were negatively correlated in wheat.

Chintu *et al*. (1994) observed positive correlations of 1000 grain weight with iron ($r = 0.80$; $P < 0.01$) and zinc ($r = 0.85$; $P < 0.01$) content per grain which indicated that breeding for higher levels of these micronutrients could be achieved without compromising the large grain size in pearl millet.

Graham and Welch (1996) reported significant and fairly higher positive correlation ($r = 0.55$) between grain iron and zinc contents suggesting the possibility of combining both the micronutrients in single agronomic background. They further noted that the seeds rich in Fe and Zn contents showed several agronomic advantages such as higher seedling vigor, especially in low- fertile soils, higher levels of resistance to diseases and empowering plants with higher water use efficiency.

Velu (2006) reported negative association of grain Fe ($r = -0.60$ to -0.31) and grain Zn ($r = -0.32$ to -0.53) with days to 50 % flowering in pearl millet.

Morgunov *et al*. (2007) found negative but non-significant association of grain iron (r = 0.05) with days to 50 % flowering and 1000-grain weight, while significant negative correlation with grain yield (r = -0.41) in wheat. He further determined the association of grain zinc with days to 50 % flowering (r = -0.13), 1000-grain weight (r = 0.03) and grain yield (r = -0.64) in wheat.

Montezano *et al*. (2008) determined that the linear correlation coefficients between nutrient content and grain yield were significant and negative for Cu, Mn and Zn in maize.

Velu *et al*. (2008) observed positive association of 1000-grain weight with grain Fe (r = 0.34 to 0.56) and grain Zn (r = 0.34 to 0.46) in pearl millet. He further found negative but non-significant association of days to 50 % flowering with grain Fe (r = -0.29) and grain Zn (r = -0.31)

Govindaraj *et al*. (2009) found that the 100-grain weight was the most important trait for maximizing grain yield owing to its high significant positive association with grain yield in pearl millet. They further identified positive correlation between grain iron and zinc, suggesting simultaneous selection of grain iron and zinc.

Gupta *et al*. (2009) found significant positive correlation between Fe and Zn content (r=0.81 to 0.82; $P<0.01$) in pearl millet suggesting the possibility of simultaneous effective genetic improvement of both micronutrients. They further reported non-significant correlation of grain iron and zinc contents with grain yield and 1000-grain weight indicating that there would be no penalty on grain yield and seed size while breeding for grains rich in these micronutrients.

Kumar *et al*. (2009) observed significant negative correlation of grain Fe (r = -0.36) and Zn contents (r = -0.46) with grain yield in sorghum.

Zhao *et al*. (2009) found negative correlation between concentration of grain zinc and grain yield and positive correlation between grain zinc and iron concentrations in wheat.

Bello (2010) observed strong positive correlation between yield components and nutritive characters (protein, carbohydrate, ash, fat and fibre) of sorghum.

Chatzav *et al*. (2010) reported positive correlations among the concentrations of grain zinc, iron and protein in wheat, suggesting that all the three nutrients can be improved concurrently with no yield penalty.

Kumar *et al*. (2010) observed highly significant positive correlation between grain iron and zinc content (r = 0.853; $P<0.01$). They also observed weak association of grain Fe and Zn with days to 50 % flowering, plant height, grain yield and grain size indicating that there would be no penalty for enhancing grain Fe and Zn contents in sorghum along with other agronomic traits such as grain size and grain yield in varied maturity backgrounds.

Na *et al.* (2010) reported a negative genetic correlation between micronutrient content and 1000-grain weight and positive phenotypic correlation between micronutrient content and grain yield of wheat and further stated that the possibility for simultaneously improving grain contents of micronutrients, protein and yield in wheat.

Yong *et al*. (2010) reported that grain iron concentration was highly significant and positively correlated with that of Zn in wheat, indicating high possibility to combine high Fe and Zn traits in wheat breeding. They further found strong positive correlations among the concentrations of Fe, Zn and protein content.

Xian *et al*. (2010) observed significant and positive correlation between zinc and iron concentrations in wheat grain.

Anandan *et al.* (2011) observed negative correlation between grain yield and mineral contents and positive correlation among the mineral elements Fe, Zn, Mn and Cu in rice.

Feng *et al*. (2011) reported the positive correlations among grain Zn, Fe and protein contents in wheat, suggesting that all these three traits were combinable and could be simultaneously enhanced.

Velu *et al*. (2011) found highly significant and positive correlation between zinc and iron concentrations (r=0.81; $P<0.01$) of pearl millet, indicating that simultaneous improvement of both the micronutrients would be effective.

2.5 Path Co-efficient Analysis

Path coefficient is a standard regression coefficient, which helps in specifying the actual forces acting in the cause and effect system and indicate their relative importance, instead of simply measuring the mutual relationship. Path analysis gives additional information on the magnitude of direct and indirect effects of the characters on yield.

Gao (1984) reported that grain number/ear in sorghum had the greatest direct effect on grain yield, followed by 1000-grain weight.

Amirthadevarathinam and Sankarapandian (1994) showed that 1000 grain weight had direct influence on plant yield in sorghum and further recorded the direct effect of number of grains in the primary branch fortified by its pronounced indirect effect through length of the primary branch.

Veerabadhiran *et al*. (1994) found that the number of grains/panicle had maximum positive direct effect on yield followed by 1000 grain weight and days to 50% bloom in sorghum.

Chaudhary *et al*. (2001) reported direct effects of plant height on grain yield and high indirect effects of days to 50 % flowering via plant height in sorghum.

Sheikh and Singh (2001) found that harvest index had largest direct effect on the grain yield per plant followed by total biomass and number of grains per ear in wheat.

Deepalakshmi and Ganesamurthy (2007) observed that number of leaves per plant (0.820), earhead length (0.438), earhead weight (0.534), number of primaries per panicle (0.353) and grainmold score (0.306) had positive direct effect on seed yield. They further reported the maximum indirect effects of earhead weight were maximum through number of leaves per plant followed by number of primaries per panicle, earhead length and plant height on seed yield in sorghum.

Ezeaku and Mohammed (2006) found that head weight of sorghum had the highest direct effect on grain yield (0.961), while 1000 grain mass contributed indirectly to grain yield via head weight (0.507).

Chakraborti *et al.* (2009) observed that kernel number per ear row in maize had significant direct effect on grain yield, while kernel iron and zinc concentrations had no significant direct or indirect effects on grain yield.

Moradi and Azarpour (2011) reported that ear length was most determinative and most effective trait with a positive effect on corn yield and also had an indirect effect on yield through rows per ear and 1000 grain weight.

CHAPTER III

MATERIAL AND METHODS

Chapter III

MATERIAL AND METHODS

The present investigation was undertaken by conducting two field experiments during two *postrainy* seasons, 2010-11 and 2011-12 at ICRISAT farm, Patancheru, Hyderabad, Andhra Pradesh, India situated at 17.53^0 N latitude, 78.27^0 E longitude and altitude of 545 m above mean sea level. The experiments conducted include:

1. Heterosis and combining ability studies for grain iron content
2. Heterosis and combining ability studies for grain zinc content

The details pertaining to the generation and evaluation of experimental material and the analysis of data carried out are described below:

3.1 Generation of Breeding Material

In each experiment, four inbred lines were grown in a crossing block (Table 3.1.) and mated in a full-diallel fashion to generate twelve (6 direct and 6 reciprocal) crosses. As the sessile spikelets were bisexual, emasculation was done to remove anthers. Emasculation was done by using pencil technique in which tip of pencil is placed at the spikelet and rotated pointing upward, due to the pressure created, the anthers come out from the top of the spikelet and anthers are removed using forceps. Immediately after emasculation, the flower or inflorescence was covered with craft bags to prevent random cross-pollination.

Viable pollen from panicles of male parents was then gently collected in butter paper bags by tapping the panicles and dusted the pollen over the female parents until adequate pollen was deposited on the stigmas of the emasculated spikelets. This was normally done in the morning hours during anthesis. The pollinated spikelets were then covered with fresh butter paper bags immediately after dusting to prevent further cross pollination if any.

Table 3.1. Crossing block of parents in full-diallel mating design

Parents	P_1	P_2	P_3	P_4
P_1	S_1	H_1 (DC_1)	H_2 (DC_2)	H_3 (DC_3)
P_2	H_4 (RC_1)	S_2	H_5 (DC_4)	H_6 (DC_5)
P_3	H_7 (RC_2)	H_8 (RC_3)	S_3	H_9 (DC_6)
P_4	H_{10} (RC_4)	H_{11} (RC_5)	H_{12} (RC_6)	S_4

Where, P = Parent H = Hybrid S = Selfing

DC = Direct Cross RC = Reciprocal Cross

3.2 Evaluation of Experimental Material

The evaluation of the hybrids along with their parental lines and standard check was carried out experimentwise for two successive *postrainy* seasons, 2010-11 and 2011-12. During *postrainy* season, 2010-11, the evaluation was carried out using the experimental material that was already generated during *postrainy* season, 2009-10 in ICRISAT farm. The evaluation was conducted for second time during *postrainy* season, 2011-12 using the same parents, check and the crosses that were generated from the crossing programme of *postrainy* season, 2010-11 to confirm the results obtained in the previous year.

The experimentwise details pertaining to the parents used, methodology adopted and collection of data are furnished below:

3.2.1 Experiment-I: Heterosis and Combining Ability Studies for Grain Iron Content

3.2.1.1 Material: Four inbred lines with diversified levels of grain iron content were mated in a full-diallel fashion to generate twelve (6 direct and 6 reciprocal) crosses. The details of the parental lines used in this experiment are furnished in Table 3.2.

Table 3.2. Details of parents with diversified levels of grain iron content

Parental line	Pedigree	Iron density (mg kg^{-1})
IS 2263	Landrace collected from United States of America	34.83
IS 13211	Landrace collected from United States of America	35.39
IS 10305	Landrace collected from India	30.50
SPV 1359	RSLG 112-1-6	28.87
Check (ICSR 40)	(UChV2 X E35-1)-11-3-4	41.38

3.2.1.2 Methodology: Four parental lines and twelve hybrids along with a standard check were evaluated for grain iron content and five important traits in a Randomized Block Design (RBD) with three replications in field under high fertility conditions during two successive *postrainy* seasons, 2010 and 2011.

Each entry was sown in two row plots of 2 m length with 75 cm spacing between the rows and 10 cm between the plants, making the plot size of 1.5 m^2. Two seeds were planted/hill with a spacing of 10 cm between the hills and thinned later to a single seedling/hill to obtain a population stand of 40 plants/plot. The crop was supplied with a fertilizer dose of 80 kg N and 40 kg P_2O_5 per hectare and nitrogen was applied in three split doses. 4 to 5 irrigations were given as and when required during the cropping season. Recommended and usual cultural practices were adopted to raise a good crop.

3.2.1.3 Collection of data: The observations on the below mentioned characters were recorded as per the standard techniques at appropriate growth stages, replicationwise in each plot on all the parameters except on plant height for which observations were taken on five plants selected randomly in each genotype in each replication and the mean of those five plants were utilized for carrying out statistical analysis.

3.2.1.3.1 Plant height (m): Plant height was measured in metres by using a meter scale from base of the plant to the tip of the flag leaf in each hill at the time of harvest.

3.2.1.3.2 Days to 50 % flowering: The numbers of days taken from the day of sowing to first flowering in 50 per cent of plants were counted and recorded as days to 50 per cent flowering in each plot and in each replication.

3.2.1.3.3 Plant aspect score: The agronomic desirability score was recorded on a scale of 1 to 5, where 1 = most desirable and 5 = least desirable was recorded in each plot and in each replication.

3.2.1.3.4 100-grain weight (g): One hundred well filled grains were counted at random from each genotype per replication and weighed after thorough drying to 12 per cent moisture content and recorded in grams, with the help of electronic top pan balance (Precision of 0.01 g).

3.2.1.3.5 Grain yield (t ha^{-1}): The weight of filled grains harvested from the entire plot was recorded in grams after drying the grains to the required moisture content (12 %) and converted into tonnes per hectare.

3.2.1.3.6 Grain iron content (mg kg^{-1}): The panicles were harvested at maturity and the grain was threshed carefully without any contact with metal containers to avoid contamination. The cleaned seeds were collected in cloth bags and the iron content in them was measured with Oxford X-supreme 8000 model X-ray flourescence analyzer (XRF). Ten samples (each sample of 5-8 g.) were measured at a time and the grain iron content was displayed on the screen in mg kg^{-1}.

3.2.1.3.6.1 Working principle of X-ray flourescence analyzer: This is a non-destructive bulk composition measurement instrument based on the X-ray flourescence principle. X-ray flourescence spectrometry is a technique used broadly for elemental analysis. During analysis, materials of interest are bombarded with X-rays energetic enough to eject one or more electrons from component atoms (thus ionizing them). Whenever an electron from inner orbital is ejected, electrons from higher energy orbitals fall to the lower energy orbital. An X-ray photon equal to the difference in energy of the orbitals is released. Thus, individual elements exposed to ionizing radiation emit photons of characteristic energies. For each element, the intensity of emitted radiation is proportional to the concentration of that element in the sample.

3.2.2 Experiment-II: Heterosis and Combining Ability Studies for Grain Zinc Content

3.2.2.1 Material: Four inbred lines with varied levels of grain zinc content were mated in a full-diallel fashion to generate twelve (6 direct and 6 reciprocal) crosses. The details of the parental lines used in this experiment are furnished in Table 3.3.

Table 3.3. Details of parents with diversified levels of grain zinc content

Parental line	Pedigree	Zinc density (mg/kg)
IS 2248	Landrace collected from India	45.70
IS 20843	Landrace collected from United States of America	40.15
PVK 801	[(IS 23528 X SPV 475) X (PS 29154)]-4-2-2-4	36.10
ICSB 56	WAE 1067-3-5-1	29.72
Check (ICSR 40)	(UChV2 X E35-1)-11-3-4	29.90

3.2.2.2 Methodology: Same as described in 3.2.1.2.

3.2.2.3 Collection of data: The observations on the below mentioned characters were recorded as per the standard techniques at appropriate growth stages, replicationwise in each plot.

3.2.2.3.1 Plant height (m): Same as mentioned in 3.2.1.3.1.

3.2.2.3.2 Days to 50 % flowering: Same as described in 3.2.1.3.2.

3.2.2.3.3 Plant aspect score: Same as furnished in 3.2.1.3.3.

3.2.2.3.4 100-grain weight (g): Same as given in 3.2.1.3.4.

3.2.2.3.5 Grain yield (t ha^{-1}): Same as described in 3.2.1.3.5.

3.2.2.3.6 Grain zinc content (mg kg^{-1}): The panicles were harvested at maturity and the grain was threshed carefully without any contact with metal containers to avoid contamination. The cleaned seeds were collected in cloth bags and the zinc content in them was measured with Oxford X-supreme 8000 model X-ray flourescence analyzer (XRF). Ten samples (each sample of 5-8 g.) were measured at a time and the grain zinc content was displayed on the screen in mg kg^{-1}.

3.3 Statistical Analysis

The data recorded on different traits was subjected to the following statistical analysis using SAS (version 9.2). Since, the data recorded on some observations *i.e.*, plant height, days to 50 % flowering and plant aspect score in experiment-I and days to 50 % flowering and grain yield in experiment-II was significantly varied across the seasons due to environmental influence, homgenity test of variance was conducted to nullify the environmental influence and statistical analysis was done using that transformed data.

3.3.1 Analysis of Variance

The analysis of variance was carried out for Randomized Block Design (RBD) with three replications as suggested by Panse and Sukhatme (1985).

$$Y_{ij} = m + g_i + r_j + e_{ij}$$

Where,

Y_{ij} = Phenotypic observation of i^{th} genotype in j^{th} replication

m = General mean

g_i = Effect of i^{th} genotype

r_j = Effect of j^{th} replication

e_{ij} = Random error

The analysis of variance is as follows:

Source	**d.f.**	**MS**	**F calculated**
Replications (r)	(r-l)	*Mr*	*Mr/Me*
Treatments (t)	(t-l)	*Mt*	*Mt/Me*
Error (e)	(r-l) (t-l)	*Me*	
Total	(rt-l)		

Where,

r = number of replications

t = number of treatments (genotypes)

Mr = mean sum of squares of replications

Mt = mean sum of squares of treatments

Me = mean sum of squares of error

df = degrees of freedom

MS = mean sum of squares

The significance of mean sum of squares for each character was tested against the corresponding error degrees of freedom using 'F' test (Fisher and Yates, 1963).

3.3.2 Pooled Analysis of Variance

Pooled analysis of variance for each character was done as per the SAS program (version 9.2) and the analysis of variance is as depicted below:

Source	d.f.	MS	F calculated
Replication	(r-2)	*Mr*	Mr/Me^1
Genotypes (G)	(t-1)	*Mt*	Mt/Me^1
Environments (E)	(e-1)	*Me*	Me/Me^1
G X E interaction	(t-1) (e-1)	*Mge*	Mge/Me^1
Pooled error	(r-2) (t-1)	Me^1	

Where,

r = total number of replications in two environments

t = number of treatments (genotypes)

Mr = mean sum of squares of replications

Mt = mean sum of squares of treatments

Me = mean sum of squares of environment

Mge = mean sum of squares of genotype environment interaction

Me^1= mean sum of squares of pooled error

df = degrees of freedom

MS = mean sum of squares

3.3.3 Estimation of Heterosis

Heterosis was estimated for twelve hybrids for five characters in each experiment using the following formulae.

3.3.3.1 Heterosis over Mid Parent: Heterosis was expressed as per cent increase or decrease observed in the F_1 over the mid-parent as per the following formula.

$$\text{Heterosis over mid parent (\%)}\ (H_1) = \frac{\overline{F}_1 - \overline{MP}}{\overline{MP}} x100$$

Where,

$\overline{F}_1$ = Mean of F_1

$\overline{MP}$ = Mean of parents

3.3.3.2 Heterosis over Better Parent: Heterosis over better parent was expressed as per cent increase or decrease observed in F_1 over the better parent.

$$\text{Heterosis over better parent (\%)}\ (H_2) = \frac{\overline{F}_1 - \overline{BP}}{\overline{BP}} x100$$

Where,

$\overline{BP}$ = Mean of better parent (for days to 50% flowering, earliness is desirable so the early parents are taken as better parents).

3.3.3.3 Heterosis over standard check: Heterosis over standard check was expressed as per cent increase or decrease observed in F_1 over standard check.

$$\text{Heterosis over standard check (\%)}\ (H_3) = \frac{\overline{F}_1 - \text{Mean of check}}{\text{Mean of check}} x100$$

3.3.3.4 Test of significance of heterosis: To test the significance for different types of heterosis needs computation of standard error (SEm). The significance of heterosis over mid-parent, better parent and standard check was then tested by comparing the calculated 't'- value with the tabulated student's 't' value for appropriate error degrees of freedom at 5 per cent and 1 per cent level of significance (0.05 and 0.01 level of probability). The differences in the magnitude of heterosis were tested, following the procedure given by Panse and Sukhatme (1985).

$$\text{'t'}_{cal} \text{ for mid-parent heterosis} = \frac{\text{Mean of } F_1 \text{- Mean of mid-parent}}{\text{SEm}}$$

$$\text{SEm} = \frac{\sqrt{3\text{EMS}}}{2r}$$

$$\text{t'}_{cal} \text{ for better parent heterosis} = \frac{\text{Mean of } F_1 \text{- Mean of better parent}}{\text{SEm}}$$

$$\text{SEm} = \frac{\sqrt{2\text{EMS}}}{r}$$

$$\text{t'}_{cal} \text{ for standard heterosis} = \frac{\text{Mean of } F_1 \text{- Mean of standard check}}{\text{SEm}}$$

$$SEm = \frac{\sqrt{2EMS}}{r}$$

Where,

EMS = Error mean of squares

r = Number of replications

3.3.3.5 Least Significance Difference (Critical Difference) for Heterosis

The significance of the difference between two estimates of heterosis were tested by computing the least significant difference (LSD) by multiplying the SEm with the appropriate student's 't' value of respective error degrees of freedom at desired level of probability.

CD = SE m x 't' table value at error degrees of freedom

Where, SEm = Standard error

3.3.4 Combining Ability Analysis

The combining ability with one set of hybrids and parents was worked out according to Method-I and Model-I (fixed effects model) given by Griffing (1956).

$$Y_{ij} = m+g_i+g_j+s_{ij}+r_{ij}+1/bc\sum\sum e_{ijkl}$$

Where,

Y_{ij} = mean of i × jth genotype over k and l

m = population mean

g_i = *gca* effect of i_{th} parent

g_j = *gca* effect of j_{th} parent

s_{ij} = interaction *i.e., sca* effect

r_{ij} = reciprocal effect and

e_{ijkl} = mean error effect

The analysis of variance is as follows:

Source	Degrees of freedom	Mean sum of squares
GCA	p-1	M_g
SCA	p (p-1)/2	M_s
Reciprocals	p (p-1)/2	M_r
Error	(t-1) (r-1)	M_e^1

Where, p = number of parents

t = number of treatments (parents and their crosses)

r = number of replications

M_g = mean squares due to GCA

M_s = mean squares due to SCA

M_r = mean squares due to RCA

M_e^1= mean squares due to error

3.3.4.1 Estimation of General and Specific Combining Ability Effects: The *gca* of the parents (g_i) and the *sca* (s_{ij}) of the crosses were calculated as follows:

g_i (*gca* of i^{th} parent) = $1/2n\ (Y_{i.}+Y_{.i})-1/n^2 Y..$

s_{ij} (*sca* of the cross i X j^{th} parent) = $½\ (Yij+ Yji) – 1/2n\ (Y_{i.}+Y_{.i}+Y_{j.}+Y_{ij}) + 1/n^2 Y..$

r_{ij} (reciprocal effect of the cross i X j^{th} parent) = $½(Yij – Yji)$.

Where,

n = Number of parents used in diallel mating design

Yi. = Female array total of the common parent

Y.j = Male array total of the common parent

Y.. = Overall total of the diallel table

3.3.4.2 Test of significance of general and specific combining ability effects: To test the significance for *gca*, *sca* and reciprocal effects, standard error was need to be calculated. Their significance was then tested by comparing the calculated 't'- value with the tabulated student's 't'-value for appropriate error degrees of freedom at 5 per cent and 1 per cent level of significance (0.05 and 0.01 level of probability), respectively.

$$S.E gi = \sqrt{\frac{(p-1)\ M_e^1}{2p^2}}$$

$$S.E sij = \sqrt{\frac{(p-1)^2\ M_e^1}{p^2}}$$

$$S.E rji = \sqrt{\frac{M_e^1}{2}}$$

Calculated 't'- value for *gca* effect = $\frac{g_i}{S.E gi}$

for *sca* effect = $\frac{s_i}{S.E sij}$

For reciprocal effect = $\frac{r_i}{S.E rji}$

3.3.4.3 Estimation of General and Specific Combining Ability Variances: The variances of GCA and SCA were calculated using the following formulae.

$$\text{GCA variance } (\sum gi^2) = \frac{M_g - M_g}{2p}$$

$$\text{SCA variance } (\sum sij^2) = M_g – M_e$$

RCA variance ($\sum rji^2$) = $M_r - M_e$

Where,

p = number of parents

M_g = mean squares due to GCA

M_s = mean squares due to SCA

M_r = mean squares due to RCA

M_e^1 = mean squares due to error

3.3.4.4 Estimation of Predictability Ratio

Predictability ratio was computed using the following formula (Baker, 1978)

$$\text{Predictability ratio} = \frac{2\sigma^2 gca}{(2\sigma^2 gca + \sigma^2 sca)}$$

Closer the predictability ratio to unity, better is the predictability of the crosses performed based on *gca* effects of their parents, which means predominance of additive genetic variance for that trait.

3.3.5 Correlations

Correlation coefficients were calculated at genotypic and phenotypic level using the formulae suggested by Falconer (1981).

$$\text{Genotypic coefficient of correlation } (r_g) = \frac{\sigma_g\,(x.y)}{\sqrt{\sigma^2_{gx}\,.\,\sigma^2_{gy}}}$$

Where,

$\sigma_g\,(x.y)$ = genotypic covariance between the variables x and y

σ^2_{gx} = genotypic variance of 'x'

σ^2_{gy} = genotypic variance of 'y'

$$\text{Genotypic variance} = \frac{\text{Treatment MS} - \text{Error MS}}{\text{Number of replications}}$$

Similarly,

$$\text{Genotypic covariance} = \frac{\text{Treatment Cov} - \text{Error Cov}}{\text{Number of replications}}$$

$$\text{Phenotypic coefficient of correlation } (r_g) = \frac{\sigma_p\,(x.y)}{\sqrt{\sigma^2_{px}\,.\,\sigma^2_{py}}}$$

Where,

$\sigma_p\,(x.y)$ = phenotypic covariance between the variables *x* and *y*

σ^2_{px} = phenotypic variance of '*x*'

σ^2_{py} = phenotypic variance of 'y'

3.3.6 Path Coefficient Analysis

The direct and indirect effects both at genotypic and phenotypic levels were estimated by taking grain iron and zinc contents as dependent variables, using path coefficient analysis suggested by Wright (1921) and Dewey and Lu (1959). The following equations were formed and solved simultaneously for estimating the various direct and indirect effects.

$$r1y = P1y\ r11 + P2y\ r12 + P3y\ r13 \ldots\ldots\ldots + Pny\ r1n$$

$$r2y = P1y\ r21 + P2y\ r22 + P3y\ r23 \ldots\ldots\ldots + Pny\ r2n$$

$$\begin{matrix} . & . & . & . & . \\ : & : & : & : & : \end{matrix}$$

$$rny = P1y\ rn1 + P2y\ rn2 + P3y\ rn3 \ldots\ldots\ldots + Pny\ r3n$$

Where,

1, 2 ……………..n = Independent variables

y = Dependant variable

r_{1y}, r_{2y} ……….. r_{ny} = Coefficient of correlation between casual factors `1` to `n` on dependent character 1

P_{1y}, P_{2y} …… P_{ny} = Direct effect of character 1 to n on character Y

The above equation can be written in matrix form as:

A C B

$$\begin{pmatrix} r_{1y} \\ r_{2y} \\ . \\ . \\ . \\ r_{ny} \end{pmatrix} \quad \begin{pmatrix} 1 & r_{12} & r_{13} & \ldots\ldots\ r_{1n} \\ r_{21} & 1 & r_{23} & \ldots\ldots\ r_{2n} \\ . & . & . & \\ . & . & . & \\ . & . & . & \\ r_{n1} & r_{n2} & r_{n3} & \ldots\ldots\ 1 \end{pmatrix} \quad \begin{pmatrix} P_{1y} \\ P_{2y} \\ . \\ . \\ . \\ P_{ny} \end{pmatrix}$$

Then

$$B = (C)^{-1} A$$

Where, $C^{-1} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \ldots\ldots\ldots & c_{1n} \\ c_{21} & c_{22} & c_{23} \ldots\ldots\ldots & c_{2n} \\ . & . & . & . \\ : & : & : & : \\ : & : & : & : \\ c_{n1} & c_{n2} & c_{n3} \ldots\ldots\ldots & c_{nn} \end{pmatrix}$

Direct effects were as follows:

$$P_{1y} = \sum_{i=1}^{k} c_{1i} \ r_{iy}$$

$$P_{2y} = \sum_{i=1}^{k} c_{2i} \ r_{iy}$$

$$P_{ny} = \sum_{i=1}^{k} c_{3i} \ r_{iy}$$

Residual effect, which measures the contribution of characters not considered, was obtained as:

$$P_{ry} = \sqrt{1-(P_{1y}\ r_{iy}) - (P_{2y}\ r_{iy}) - \ldots\ldots - P_{ny}\ r_{ny}}$$

Where, P_{ny} = direct effect of x_n on Y

r_{iy} = correlation coefficient of x_n on Y

CHAPTER IV

RESULTS AND DISCUSSION

Chapter IV

RESULTS AND DISCUSSION

The present investigation was carried out by conducting two experiments, one with parents contrasting for grain iron and other with parents contrasting for grain zinc with an objective of identifying the relative ability of parental lines to produce desirable hybrid combinations using 4 x 4 diallel mating design. The results obtained are presented experimentwise separately hereunder:

4.1 HETEROSIS AND COMBINING ABILITY STUDIES FOR GRAIN IRON IN SORGHUM USING CONTRASTING PARENTS FOR GRAIN IRON

The data collected on six characters, *viz.*, plant height, days to 50 % flowering, plant aspect score, 100-grain weight, grain yield and grain iron content in the present study from evaluation of four parents and twelve crosses developed by crossing the parents in a full-diallel fashion along with one standard check (ICSR 40) were subjected to suitable statistical analyses and the results are presented below under the following heads.

1. Analysis of variance
2. Heterosis
3. Combining ability analysis
4. Character association
5. Path coefficient analysis

4.1.1 Analysis of Variance for Different Characters

The analysis of variance (Tables 4.1. and 4.2.) indicated the existence of significant variability among the genotypes for all the characters studied in both the seasons.

The combined analysis of variance (Table 4.3.) across the two *postrainy* seasons showed that the mean squares due to genotypes, environments and genotype x environment interaction were highly significant for all the characters except 100-grain weight. The mean squares due to environments were observed to be non-significant for 100-grain weight. Thus, it is evident that the genotypes had enough variability for all

Table 4.1. Analysis of variance for various agronomic characters and grain iron content in sorghum during *postrainy* season, 2010

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain iron (mg Kg^{-1})
Replications	2	0.05	11.35**	0.28	1.13	65.16**
Genotypes	16	0.63**	104.91**	1.03**	9.18**	94.41**
Error	32	0.06	1.10	0.11	0.35	10.43

Table 4.2. Analysis of variance for various agronomic characters and grain iron content in sorghum during *postrainy* season, 2011

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain iron (mg Kg^{-1})
Replications	2	0.04	10.06	0.01	0.32	21.37
Genotypes	16	0.74**	187.92**	1.05**	6.35**	42.89**
Error	32	0.02	10.41	0.05	0.32	9.78

* indicates significance @ 5 % level of probability;

** indicates significance @ 1 % level of probability

Table 4.3. Pooled analysis of variance for various agronomic characters and grain iron content in sorghum

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain iron (mg Kg^{-1})
Replication	4	1.50	5.63**	0.14	0.72	43.26**
Genotypes (G)	16	42.85**	53.30**	1.90**	13.36**	79.43**
Environments (E)	1	1306.29**	71408.18**	0.20	92.49**	512.87**
G X E interaction	16	9.03**	59.87**	0.19*	2.18**	57.87**
Error	64	1.00	1.00	0.08	0.33	10.11

* indicates significance @ 5 % level of probability;

** indicates significance @ 1 % level of probability

the traits to estimate the nature of genetic variation and the performance of the genotypes varied significantly across the seasons.

4.1.1.1 Mean Performance of Parents and Crosses: The mean performance of parents, hybrids and standard check for six characters (Tables 4.4., 4.5. and 4.6.) are discussed hereunder characterwise:

4.1.1.1.1 Plant Height (m): The mean values for plant height varied from 1.00 m (IS 10305 X IS 13211) to 2.53 m (SPV 1359) with a grand mean of 1.88 m in 2010, 1.00 m (IS 10305) to 2.60 m (SPV 1359 X IS 13211) with a grand mean of 1.96 m in 2011 and from 1.04 m (IS 10305) to 2.52 m (IS 2263 X SPV 1359) with a general mean of 1.22 m across the seasons. Among the parents, SPV 1359 was significantly taller than all the other parents in both the seasons and across the seasons. All the parents were significantly taller than the check in both the seasons and across the seasons. The mean values for crosses ranged from 1.00 m (IS 10305 X IS 13211) to 2.50 m (IS 2263 X SPV 1359) in 2010, from 1.57 m (IS 10305 X IS 13211) to 2.60 m (SPV 1359 X IS 13211) in 2011 and from 1.29 m (IS 10305 X IS 13211) to 2.52 m (IS 2263 X SPV 1359) across the seasons. Among the crosses, IS 2263 X SPV 1359 recorded highest plant height in 2010 (2.50 m) and across the seasons (2.52 m), while SPV 1359 X IS 13211 recorded highest plant height (2.63 m) in 2011. IS 2263 X SPV 1359 was significantly taller than all the crosses except three crosses *i.e.*, SPV 1359 X IS 10305, SPV 1359 X IS 2263 and SPV 1359 X IS 13211 in 2010, while it was significantly taller than all the crosses except SPV 1359 X IS 10305 followed by SPV 1359 X IS 2263 across the seasons. Almost all the crosses recorded significantly higher plant height in both the seasons and across the seasons than the check except IS 10305 X IS 13211 in 2010. Thus, the results obtained in the present investigation clearly indicated that the plant height of the crosses was highly influenced by the genotype of the parents. The crosses developed by involving SPV 1359 (the tallest parent) as one of the parents, were in general, taller than the remaining crosses, while the opposite results were observed with the involvement of the shortest parent, IS 10305. The taller hybrids can be utilised for dual purpose of grain and fodder. The cross, IS 10305 X IS 13211 recorded lowest plant height in both the seasons which might be due to the short stature of both of its parents.

4.1.1.1.2 Days to 50 % Flowering: Days to 50 % flowering varied from 71.33 days (IS 2263 X IS 10305) to 93 days (IS 13211 X SPV 1359) with a grand mean of 77.71 days in 2010, from 56 days (IS 13211 X IS 10305) to 83 days (IS 13211) with a grand

Table 4.4. Mean performance of parents contrasting for grain iron and their hybrids for plant height (m) and 50 % flowering in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Plant height (m)			Days to 50 % flowering		
	2010	2011	POOLED	2010	2011	POOLED
PARENTS						
IS 2263	2.03	2.20	2.12	76.00	77.33	76.67
IS 13211	1.87	1.43	1.65	77.67	83.00	80.34
IS 10305	1.07	1.00	1.04	75.33	62.67	69.00
SPV 1359	2.53	2.37	2.45	77.67	75.67	76.67
MEAN	1.88	1.75	1.81	76.67	74.67	75.67
DIRECT CROSSES						
IS 2263 X IS 13211	1.80	1.63	1.72	76.00	61.00	68.50
IS 2263 X IS 10305	1.97	1.77	1.87	71.33	69.00	70.17
IS 2263 X SPV 1359	2.50	2.53	2.52	76.67	75.00	75.84
IS 13211 X IS 10305	1.83	1.63	1.73	75.33	56.00	65.67
IS 13211 X SPV 1359	1.73	2.33	2.03	93.00	66.00	79.50
IS 10305 X SPV 1359	1.87	2.23	2.05	75.67	67.33	71.50
MEAN	1.95	2.02	1.99	78.00	65.72	71.86
RECIPROCAL CROSSES						
IS 13211 X IS 2263	1.83	1.87	1.85	78.00	60.33	69.17
IS 10305 X IS 2263	1.70	2.00	1.85	77.67	64.00	70.84
IS 10305 X IS 13211	1.00	1.57	1.29	91.33	60.00	75.67
SPV 1359 X IS 2263	2.27	2.50	2.39	75.33	75.67	75.50
SPV 1359 X IS 13211	2.23	2.60	2.42	78.00	77.00	77.50
SPV 1359 X IS 10305	2.43	2.50	2.47	76.67	66.67	71.67
MEAN	1.91	2.17	2.04	79.50	67.28	73.39
ICSR 40 (CHECK)	1.23	1.20	1.22	69.33	59.33	64.33
GRAND MEAN	1.88	1.96	1.95	77.71	68.00	72.85
C.V.%	13.22	6.79	10.01	1.35	4.75	3.05
C.D. (5%)	0.41	0.22	0.32	1.75	5.37	3.56
S Em	0.14	0.08	0.11	0.61	1.86	1.24

Table 4.5. Mean performance of parents contrasting for grain iron and their hybrids for plant aspect score and 100-grain weight (g) in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Plant aspect score			100 grain weight (g)		
	2010	2011	POOLED	2010	2011	POOLED
PARENTS						
IS 2263	2.00	2.33	2.17	3.23	3.44	3.34
IS 13211	3.00	4.00	3.50	2.67	2.22	2.45
IS 10305	2.33	2.33	2.33	1.81	2.09	1.95
SPV 1359	1.33	1.00	1.17	3.88	3.94	3.91
MEAN	2.17	2.42	2.29	2.90	2.92	2.91
DIRECT CROSSES						
IS 2263 X IS 13211	3.00	3.00	3.00	3.26	2.63	2.95
IS 2263 X IS 10305	2.00	2.33	2.17	3.13	3.07	3.10
IS 2263 X SPV 1359	2.00	1.67	1.84	3.67	3.61	3.64
IS 13211 X IS 10305	2.33	3.00	2.67	2.67	2.59	2.63
IS 13211 X SPV 1359	3.00	2.00	2.50	2.80	3.41	3.11
IS 10305 X SPV 1359	2.00	2.00	2.00	2.94	3.57	3.26
MEAN	2.39	2.33	2.36	3.08	3.15	3.11
RECIPROCAL CROSSES						
IS 13211 X IS 2263	2.33	3.00	2.67	2.89	3.11	3.00
IS 10305 X IS 2263	2.00	1.67	1.84	2.82	3.44	3.13
IS 10305 X IS 13211	2.33	3.00	2.67	1.89	2.16	2.03
SPV 1359 X IS 2263	1.67	1.33	1.50	3.61	3.74	3.68
SPV 1359 X IS 13211	2.33	1.33	1.83	3.69	3.77	3.73
SPV 1359 X IS 10305	2.00	1.67	1.84	3.56	3.38	3.47
MEAN	2.11	2.00	2.06	3.08	3.27	3.17
ICSR 40 (CHECK)	2.00	2.67	2.34	3.17	2.98	3.08
GRAND MEAN	2.21	2.25	2.23	3.04	3.13	3.08
C.V.%	15.32	23.85	19.59	10.69	7.46	9.08
C.D. (5%)	0.56	0.89	0.73	0.54	0.39	0.47
S Em	0.2	0.31	0.26	0.19	0.13	0.16

Table 4.6. Mean performance of parents contrasting for grain iron and their hybrids for grain yield (t ha^{-1}) and grain iron (mg kg^{-1}) in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Grain yield (t ha^{-1})			Grain iron (mg kg^{-1})		
	2010	2011	POOLED	2010	2011	POOLED
PARENTS						
IS 2263	4.21	4.31	4.26	35.60	34.06	34.83
IS 13211	3.36	0.58	1.97	32.00	38.77	35.39
IS 10305	0.73	1.01	0.87	33.70	27.30	30.50
SPV 1359	6.97	4.98	5.98	29.10	28.63	28.87
MEAN	3.82	2.72	3.27	32.60	32.19	32.40
DIRECT CROSSES						
IS 2263 X IS 13211	4.59	1.84	3.22	38.53	34.00	36.27
IS 2263 X IS 10305	6.25	3.31	4.78	35.73	31.38	33.56
IS 2263 X SPV 1359	5.24	4.62	4.93	41.40	27.93	34.67
IS 13211 X IS 10305	4.02	1.24	2.63	44.30	27.27	35.79
IS 13211 X SPV 1359	3.94	2.71	3.33	35.43	37.10	36.27
IS 10305 X SPV 1359	7.09	3.24	5.17	29.17	28.30	28.74
MEAN	5.19	2.83	4.01	37.43	31.00	34.21
RECIPROCAL CROSSES						
IS 13211 X IS 2263	4.52	1.84	3.18	42.57	34.25	38.41
IS 10305 X IS 2263	4.54	2.79	3.67	28.27	31.13	29.70
IS 10305 X IS 13211	2.51	0.99	1.75	33.03	27.85	30.44
SPV 1359 X IS 2263	6.41	5.07	5.74	31.23	31.55	31.39
SPV 1359 X IS 13211	5.68	3.99	4.84	34.47	26.92	30.70
SPV 1359 X IS 10305	6.93	3.18	5.06	33.07	27.82	30.45
MEAN	5.10	2.98	4.04	33.77	29.92	31.85
ICSR 40 (CHECK)	3.03	1.95	2.49	47.83	34.93	41.38
GRAND MEAN	4.71	2.80	3.76	35.61	31.13	33.37
C.V.%	12.53	20.23	16.38	9.07	10.05	9.56
C.D. (5%)	0.98	0.94	0.96	5.37	5.20	5.29
S Em	0.34	0.33	0.34	1.86	1.81	1.84

mean of 68 days in 2011 and from 65.67 days (IS 13211 X IS 10305) to 80.34 days (IS 13211) with a general mean of 72.85 days across the seasons. Among the parents, IS 10305 was the earliest and it was significantly earlier than all other parents in both the seasons and across the seasons except IS 2263 in 2010. Among the hybrids, IS 2263 X IS 10305 was the earliest (71.33 days) in 2010 and it was significantly earlier than all other crosses, while IS 13211 X IS 10305 (56.00 days) was the earliest in 2011 and significantly earlier than all other crosses except IS 2263 X IS 13211, IS 13211 X IS 2263 and IS 10305 X IS 13211. Across the seasons, IS 13211 X IS 10305 was the earliest and significantly earlier than all crosses except IS 2263 X IS 13211 and IS 13211 X IS 2263. Compared with standard check, all the genotypes exhibited delayed flowering in both the seasons.

4.1.1.1.3 Plant Aspect Score: The plant aspect score ranged from 1.33 (SPV 1359) to 3.00 (IS 13211, IS 2263 X IS 13211 and IS 13211 X SPV 1359) with a grand mean of 2.21 in 2010, from 1.00 (SPV 1359) to 4.00 (IS 13211) with a grand mean of 2.25 in 2011 and from 1.17 (SPV 1359) to 3.50 (IS 13211) with a general mean of 2.23 across the seasons. SPV 1359 was agronomically more desirable while, IS 13211 was agronomically least preferable among the parents in both the seasons and across the seasons compared to check and all other parents. Among the crosses, SPV 1359 X IS 2263 was the most desirable cross in 2010 and significantly superior than IS 2263 X IS 13211, IS 13211 X IS 10305, IS 13211 X SPV 1359, IS 13211 X IS 2263, IS 10305 X IS 13211 and SPV 1359 X IS 13211. However, none of the crosses were agronomically desirable when compared to check in 2010, while SPV 1359 X IS 13211 was most desirable in 2011 and significantly superior than IS 2263 X IS 13211, IS 13211 X IS 10305, IS 13211 X IS 2263, IS 10305 X IS 13211 and IS 2263 X IS 10305. SPV 1359 X IS 2263 was the most desirable cross across the seasons and significantly desirable than IS 2263 X IS 13211, IS 13211 X IS 10305, IS 13211 X IS 2263, IS 13211 X SPV 1359 and IS 10305 X IS 13211 and also check. SPV 1359 X IS 2263, SPV 1359 X IS 13211, IS 2263 X SPV 1359 and IS 10305 X IS 2263 were significantly superior to check with respect to plant aspect score across the seasons.

4.1.1.1.4 100-Grain Weight (g): 100-grain weight varied from 1.81 g (IS 10305) to 3.88 g (SPV 1359) with a grand mean of 3.04 g in 2010, from 2.09 g (IS 10305) to 3.94 g (SPV 1359) with a grand mean of 3.13 g in 2011 and from 1.95 g (IS 10305) to 3.91 g (SPV 1359) with a general mean of 3.08 g across the seasons. SPV 1359 recorded the highest grain weight among the parents and also recorded significantly higher grain weight than all other parents and check in both the seasons and across the seasons. In addition to this, IS 2263 recorded significantly higher grain weight than check in 2011. Since, SPV 1359 had bold grains, the crosses *viz.*, SPV 1359 X IS 13211 recorded the highest grain weight followed by IS 2263 X SPV 1359 in 2010 and SPV 1359 X IS 13211 followed by SPV 1359 X IS 2263 in 2011 and across the seasons. As SPV 1359 followed by IS 2263 possessed higher grain weight than the check, most of the crosses involving SPV 1359 and IS 2263 as one of the parents exhibited higher grain weight than the check in both the seasons and across the seasons. SPV 1359 X IS 13211 recorded significantly higher grain weight than all other crosses except IS 2263 X SPV 1359, SPV 1359 X IS 2263, SPV 1359 X IS 10305 and IS 2263 X IS 13211 in 2010, while it recorded significantly higher grain weight than all other crosses except SPV 1359 X IS 2263, IS 2263 X SPV 1359, IS 10305 X SPV 1359, IS 10305 X IS 2263 and IS 13211 X SPV 1359 in 2011. Across the seasons, the same cross was significantly higher in grain weight than all other crosses except SPV 1359 X IS 2263, IS 2263 X SPV 1359 and SPV 1359 X IS 10305. None of the crosses recorded significantly higher grain weight than the check in 2010. More than 50 % of the crosses in 2010, six crosses (SPV 1359 X IS 13211, SPV 1359 X IS 2263, IS 10305 X SPV 1359, IS 10305 X IS 2263, IS 13211 X SPV 1359 and SPV 1359 X IS 10305) in 2011 and four crosses (SPV 1359 X IS 13211, SPV 1359 X IS 2263, IS 2263 X SPV 1359 and SPV 1359 X IS 10305) across the seasons recorded significantly higher grain weight than the check.

4.1.1.1.5 Grain Yield (t ha^{-1}): The mean values of grain yield ranged from 0.73 t ha^{-1} (IS 10305) to 7.09 t ha^{-1} (IS 10305 X SPV 1359) with a grand mean of 4.71 t ha^{-1} in 2010, from 0.58 t ha^{-1} (IS 13211) to 5.07 t ha^{-1} (SPV 1359 X IS 2263) with a grand mean of 2.80 t ha^{-1} in 2011 and from 0.87 t ha^{-1} (IS 10305) to 5.98 t ha^{-1} (SPV 1359) with a general mean of 3.76 t ha^{-1} across the seasons. Among the parents, the highest grain yield was recorded by SPV 1359 in both the seasons and across the seasons. SPV 1359 recorded significantly higher grain yield than all other parents and check in 2010, while SPV 1359 followed by IS 2263 exhibited significantly higher grain yield than the other parents in 2011 and across the seasons. In 2010, IS 10305 X SPV 1359 recorded highest grain yield followed by SPV 1359 X IS 10305 and SPV 1359 X IS 2263 recorded highest grain yield followed by IS 2263 X SPV 1359 in 2011 and across the seasons among the crosses. IS 10305 X SPV 1359 recorded highest grain yield and significantly higher grain yield than all other crosses except SPV 1359 X IS 10305, SPV 1359 X IS 2263 and IS 2263 X IS 10305 in 2010, while SPV 1359 X IS 2263 exhibited highest grain yield and significantly higher grain yield than all other crosses except IS 2263 X SPV 1359 and its reciprocal cross in 2011 and all other crosses except IS 10305 X SPV 1359, SPV 1359 X IS 10305 and SPV 1359 X IS 13211 across the seasons.

4.1.1.1.6 Grain Iron (mg kg^{-1}): Grain iron widely varied from 28.27 mg kg^{-1} (IS 10305 X IS 2263) to 44.30 mg kg^{-1} (IS 13211 X IS 10305) with a grand mean of 35.61 mg kg^{-1} in 2010, from 26.92 mg kg^{-1} (SPV 1359 X IS 13211) to 38.77 mg kg^{-1} (IS 13211) with a grand mean of 31.13 mg kg^{-1} in 2011 and from 28.74 mg kg^{-1} (IS 10305 X SPV 1359) to 38.41 mg kg^{-1} (IS 13211 X IS 2263) with a general mean of 33.37 mg kg^{-1} across the seasons. The highest grain iron was found in IS 2263 (35.60 mg kg^{-1}) followed by IS 10305 (33.70 mg kg^{-1}) in 2010 and IS 13211 (38.77 mg kg^{-1}) followed by IS 2263 (34.06 mg kg^{-1}) in 2011 and across the seasons. Among the crosses, IS 13211 X IS 10305 achieved highest grain iron (44.30 mg kg^{-1}) followed by IS 13211 X IS 2263 in 2010 and IS 13211 X SPV 1359 (37.10 mg kg^{-1}) followed by IS 13211 X IS 2263 in 2011. However, IS 13211 X IS 2263 recorded highest grain iron (38.41 mg kg^{-1}) followed by IS 2263 X IS 13211 and IS 13211 X SPV 1359 across the seasons (Fig 4.1). None of the parents and crosses recorded higher grain iron than check in both the seasons and across the seasons. Among the parents, IS 2263 in 2010 and IS 13211 in 2011 and across the seasons were significantly higher in grain iron than SPV 1359. In 2010, IS 13211 X IS 10305 recorded significantly higher grain iron than all crosses except IS 2263 X SPV 1359 and IS 13211 X IS 10305, while IS 13211 X SPV 1359 recorded significantly higher grain iron than all crosses except IS 2263 X IS 13211 and its reciprocal cross in 2011. However, IS 13211 X IS 2263 was significantly higher in grain iron than SPV 1359 X IS 13211, SPV 1359 X IS 10305, SPV 1359 X IS 2263, IS 10305 X IS 13211, IS 10305 X SPV 1359 and IS 10305 X IS 2263 across the seasons.

4.1.2 Heterosis

Heterosis is defined as the superiority in performance of hybrids over its parents, largely explained either due to dominance or over dominance effects. From practical standpoint, this definition of heterosis must translate into heterosis over better parent. Thus, for calculating heterosis over better parent for traits like plant height, 100-grain weight, grain yield and grain iron and grain zinc concentrations, better parents would be those that have higher values, while for days to 50 per cent flowering better parent would be the one with lower value. The dominance model assumes that each of the inbred lines contains a combination of dominance and recessive alleles at

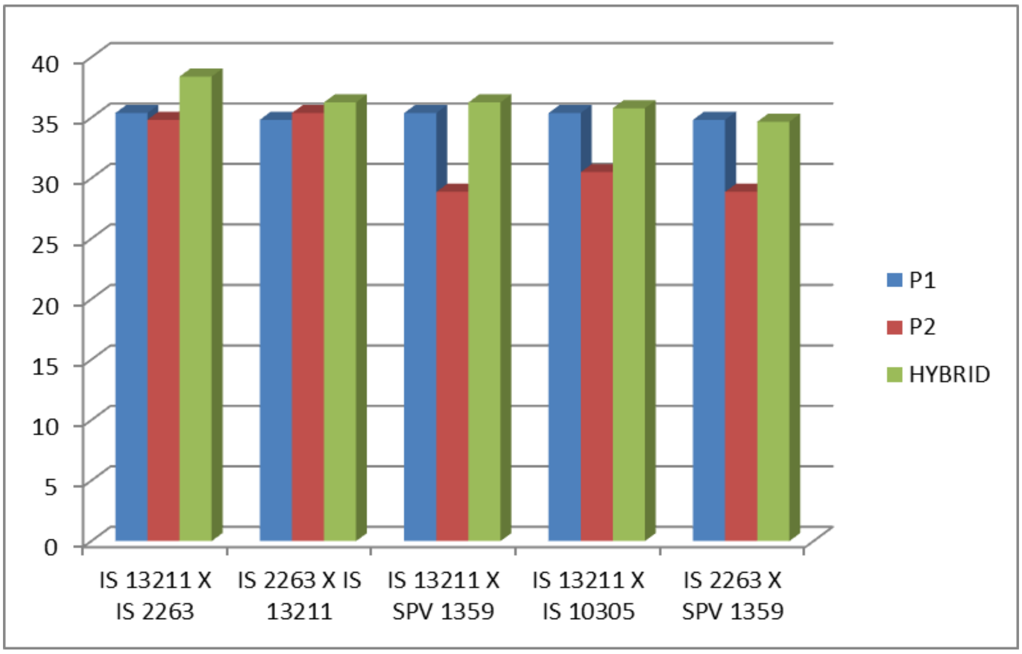

Figure 4.1. ***Per se*** **performance of promising hybrids along with parents for grain iron across the seasons**

P1 = Parent 1 **P2 = Parent 2**

different loci, which together in the F_1 hybrid, lead to heterosis (Davenport, 1908 and Jones, 1918). The over dominance model suggests the heterozygous combination of alleles at a given locus is phenotypically superior to either of the homozygous combinations at that locus. The hybrid with either positive or negative heterosis over the mid-parent indicates partial dominance of alleles either with positive or negative effect. The magnitude of heterosis largely depends on the genetic diversity among the parents used in hybridization programme. The hybrid with significant heterosis either in positive or negative direction over mid-parent indicates the dominance of positive or negative genes. Similarly, the hybrid with significant positive or negative heterosis over better parent indicates over dominance of positive or negative genes. The hybrids with non-significant mid-parent heterosis reveal the involvement of additive gene effects.

Heterosis of different quantitative traits among direct crosses and reciprocal crosses are presented in Tables 4.7 to 4.11 and are discussed hereunder:

4.1.2.1 Plant Height: Plant height of varieties or hybrids is always of greater importance to plant breeders, particularly when sorghum is grown for dual purpose and in intercropping system. Increased plant height has direct relation with grain yield and total biomass production (Thombre and Patil, 1985). Heterosis over mid-parent for this trait varied from -31.82 % (IS 10305 X IS 13211) to 35.19 % (SPV 1359 X IS 10305) in 2010, from -10.09 % (IS 2263 X IS 13211) to 48.51 % (SPV 1359 X IS 10305) in 2011 and from -40.06 % (SPV 1359 X IS 2263) to 85.45 % (IS 10305 X IS 13211) across the seasons. IS 10305 X IS 13211 and IS 13211 X SPV 1359 in 2010 and SPV 1359 X IS 2263 across the seasons exhibited highly significant negative heterosis, while none of the crosses recorded significant negative heterosis in 2011. Only three crosses (SPV 1359 X IS 10305, IS 2263 X IS 10305 and IS 13211 X IS 10305) exhibited positive heterosis in 2010, while more than 50 per cent of the hybrids had significant positive heterosis in 2011 and across the seasons. Highest significant positive heterosis was exhibited by SPV 1359 X IS 10305 in both the seasons and IS 13211 X IS 10305 across the seasons.

Heterosis over better-parent varied from -46.43 % (IS 10305 X IS 13211) to -1.32 % (IS 2263 X SPV 1359) in 2010, from -25.76 % (IS 2263 X IS 13211) to 13.95 % (IS 13211 X IS 10305) in 2011 and from -43.56 % (SPV 1359 X IS 2263) to 52.60 % (IS 10305 X IS 13211) across the seasons. None of the crosses recorded significant positive heterosis over better parent in both the seasons and across the seasons. However, IS 10305 X IS 13211 recorded significant positive heterosis across

Table 4.7. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for plant height (m) in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2263 X IS 13211	1.80	-7.69	-11.48	45.95**	1.63	-10.09	-25.76**	36.11**	9.76	-9.21	-21.02**	39.61**
IS 2263 X IS 10305	1.97	26.88*	-3.28	59.46**	1.77	10.42	-19.70**	47.22**	10.59	16.05*	-14.25*	51.58**
IS 2263 X SPV 1359	2.50	9.49	-1.32	102.70**	2.53	10.95*	7.04	111.11**	14.54	10.44	3.99	108.12**
IS 13211 X IS 10305	1.83	25.00*	-1.79	48.65**	1.63	34.25**	13.95	36.11**	9.82	30.61**	7.47	40.57**
IS 13211 X SPV 1359	1.73	-21.21**	-31.58**	40.54*	2.33	22.81**	-1.41	94.44**	12.25	5.92	-12.43*	75.26**
IS 10305 X SPV 1359	1.87	3.70	-26.32**	51.35**	2.23	32.67**	-5.63	86.11**	12.14	22.10**	-13.19*	73.24**

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.7 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
RECIPROCAL CROSSES												
IS 13211 X IS 2263	1.83	-5.98	-9.84	48.65**	1.87	2.75	-15.15**	55.56**	10.70	-0.44	-13.39*	53.10**
IS 10305 X IS 2263	1.70	9.68	-16.39	37.84*	2.00	25.00**	-9.09	66.67**	10.93	19.75*	-11.51	56.41**
IS 10305 X IS 13211	1.00	-31.82**	-46.43**	-18.92	1.57	28.77**	9.30	30.56**	13.95	85.45**	52.60**	99.60**
SPV 1359 X IS 2263	2.27	-0.73	-10.53	83.78**	2.50	9.49*	5.63	108.33**	7.89	-40.06**	-43.56**	12.95
SPV 1359 X IS 13211	2.23	1.52	-11.84	81.08**	2.60	36.84**	9.86	116.67**	14.26	23.29**	1.93	104.00**
SPV 1359 X IS 10305	2.43	35.19**	-3.95	97.30**	2.50	48.51**	5.63	108.33**	14.28	43.65**	2.13	104.41**
C.D. (5%)		0.35	0.41	0.41		0.20	0.24	0.24		1.42	1.64	1.64
C.D. (1%)		0.47	0.55	0.55		0.27	0.33	0.33		1.89	2.18	2.18

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.8. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for days to 50 % flowering in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2263 X IS 13211	76	-1.08	0.00	9.62**	61.00	-23.91**	-21.12**	2.81	45.63	-6.87**	-5.25**	8.13**
IS 2263 X IS 10305	71.33	-5.73**	-5.31**	2.88*	69.00	-1.43	10.11*	16.29**	44.65	-4.73**	-2.03	5.81**
IS 2263 X SPV 1359	76.67	-0.22	0.88	10.58**	75.00	-1.96	-0.88	26.40**	48.12	-0.64	-0.09	14.02**
IS 13211 X IS 10305	75.33	-1.53	0.00	8.65**	56.00	-23.11**	-10.64*	-5.62	44.54	-6.63**	-2.27	5.54**
IS 13211 X SPV 1359	93	19.74**	19.74**	34.13**	66.00	-16.81**	-12.78**	11.24*	54.50	10.62**	11.91**	29.15**
IS 10305 X SPV 1359	75.67	-1.09	0.44	9.13**	67.33	-2.65	7.45	13.48**	46.46	-1.44	1.93	10.08**

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.8 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**
RECIPROCAL CROSSES												
IS 13211 X IS 2263	78.00	1.52	2.63*	12.50**	60.33	-24.74**	-21.98**	1.69	46.48	-5.14**	-3.49*	10.14**
IS 10305 X IS 2263	77.67	2.64*	3.10*	12.02**	64.00	-8.57*	2.13	7.87	46.89	0.05	2.89	11.11**
IS 10305 X IS 13211	91.33	19.39**	21.24**	31.73**	60.00	-17.62**	-4.26	1.12	47.59	-0.24	4.42*	12.77**
SPV 1359 X IS 2263	75.33	-1.95	-0.88	8.65**	75.67	-1.09	0.00	27.53**	52.78	8.97**	9.58**	25.06**
SPV 1359 X IS 13211	78.00	0.43	0.43	12.50**	77.00	-2.94	1.76	29.78**	49.07	-0.41	0.75	16.26**
SPV 1359 X IS 10305	76.67	0.22	1.77	10.58**	66.67	-3.61	6.38	12.36**	46.83	-0.65	2.75	10.97**
C.D. (5%)		1.51	1.75	1.75		4.64	5.36	5.36		1.42	1.64	1.64
C.D. (1%)		2.03	2.35	2.35		6.24	7.20	7.20		1.89	2.18	2.18

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.9. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for 100-grain weight in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2263 X IS 13211	3.26	10.63	1.03	2.84	2.63	-6.89	-23.38**	-11.73	2.95	2.05	-11.56	-4.23
IS 2263 X IS 10305	3.13	24.50*	-2.89	-1.16	3.07	11.16	-10.67*	2.91	3.10	17.52*	-6.90	0.81
IS 2263 X SPV 1359	3.67	3.33	-5.33	15.77	3.61	-2.12	-8.38	21.01**	3.64	0.55	-6.87	18.31*
IS 13211 X IS 10305	2.67	19.23	0.00	-15.88	2.59	20.28*	16.67*	-13.18*	2.63	19.74*	7.57	-14.57
IS 13211 X SPV 1359	2.80	-14.31	-27.69**	-11.57	3.41	10.71*	-13.45**	14.30*	3.11	-2.18	-20.51**	0.98
IS 10305 X SPV 1359	2.94	3.46	-24.16**	-7.26	3.57	18.58**	-9.31*	19.78**	3.26	11.24	-16.67**	5.85

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.9 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
RECIPROCAL CROSSES												
IS 13211 X IS 2263	2.89	-2.04	-10.54	-8.94	3.11	10.08	-9.41	4.36	3.00	3.90	-9.95	-2.49
IS 10305 X IS 2263	2.82	11.92	-12.71	-11.15	3.44	24.68**	0.19	15.42**	3.13	18.60*	-6.05	1.73
IS 10305 X IS 13211	1.89	-15.65	-29.25**	-40.48**	2.16	0.15	-2.85	-27.71**	2.02	67.43**	50.41**	19.45**
SPV 1359 X IS 2263	3.61	1.55	-6.96	13.77	3.74	1.49	-4.99	25.47**	3.68	-44.15**	-48.27**	-34.29**
SPV 1359 X IS 13211	3.69	12.68	-4.90	16.30	3.77	22.29**	-4.40	26.26**	3.73	17.34**	-4.65	21.13**
SPV 1359 X IS 10305	3.56	25.40**	-8.08	12.41	3.38	12.06*	-14.30**	13.18*	3.47	18.53**	-11.22	12.78
C.D. (5%)		0.48	0.55	0.55		0.33	0.37	0.37		0.40	0.46	0.46
C.D. (1%)		0.64	0.74	0.74		0.44	0.49	0.49		0.53	0.61	0.61

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.10. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for grain yield in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2263 X IS 13211	4.59	21.13	8.86	51.38**	1.84	-24.61	-57.23**	-5.63	3.22	3.18	-24.56*	29.03
IS 2263 X IS 10305	6.25	152.90**	48.26**	106.16**	3.31	24.44	-23.20*	69.45**	4.78	86.29**	12.12	91.77**
IS 2263 X SPV 1359	5.24	-6.23	-24.77**	73.05**	4.62	-0.43	-7.10	136.69**	4.93	-3.60	-17.41*	97.99**
IS 13211 X IS 10305	4.02	96.57**	19.54	32.56*	1.24	56.39	23.10	-36.35	2.63	85.32**	33.50	5.55
IS 13211 X SPV 1359	3.94	-23.65**	-43.42**	30.14	2.71	-2.46	-45.55**	38.74	3.33	-16.24	-44.31**	33.51
IS 10305 X SPV 1359	7.09	84.32**	1.77	134.10**	3.24	8.13	-34.96**	65.70**	5.17	50.99**	-13.53	107.29**

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.10 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**
RECIPROCAL CROSSES												
IS 13211 X IS 2263	4.52	19.28	7.20	49.06**	1.84	-24.61	-57.23**	-5.63	3.18	2.06	-25.38*	27.63
IS 10305 X IS 2263	4.54	83.94**	7.83	49.94**	2.79	4.76	-35.34**	42.66	3.67	42.88**	-14.00	47.09*
IS 10305 X IS 13211	2.51	22.68	-25.40	-17.27	0.99	24.11	-2.31	-49.49*	1.75	23.08	-11.34	-29.90
SPV 1359 X IS 2263	6.41	14.63	-8.03	111.55**	5.07	9.12	1.81	159.39**	5.74	12.16	-3.91	130.37**
SPV 1359 X IS 13211	5.68	10.04	-18.46*	87.57**	3.99	43.61**	-19.83*	104.27**	4.84	21.78*	-19.03	94.11**
SPV 1359 X IS 10305	6.93	80.16**	-0.53	128.82**	3.18	6.13	-36.17**	62.63*	5.06	47.77**	-15.37*	102.88**
C.D. (5%)		0.86	0.98	0.98		0.81	0.94	0.94		0.82	0.94	0.94
C.D. (1%)		1.15	1.31	1.31		1.10	1.26	1.26		1.09	1.25	1.25

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.11. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for grain iron in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2263 X IS 13211	38.53	14.00*	8.24	-19.44**	34.00	-6.62	-12.30	-2.67	36.27	3.31	2.50	-12.36
IS 2263 X IS 10305	35.73	3.13	0.37	-25.30**	31.38	2.30	-7.85	-10.16	33.56	2.74	-3.65	-18.91**
IS 2263 X SPV 1359	41.40	27.98**	16.29*	-13.45*	27.93	-10.88	-17.98*	-20.04**	34.67	8.85	-0.46	-16.23*
IS 13211 X IS 10305	44.30	34.86**	31.45**	-7.39	27.27	-17.46*	-29.66**	-21.95**	35.78	8.63	1.13	-13.53*
IS 13211 X SPV 1359	35.43	15.97*	10.72	-25.93**	37.10	10.09	-4.30	6.20	36.27	12.89	2.49	-12.37
IS 10305 X SPV 1359	29.17	-7.11	-13.45	-39.02**	28.30	1.19	-1.16	-18.99*	28.73	-3.20	-5.79	-30.57**

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.11 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
RECIPROCAL CROSSES												
IS 13211 X IS 2263	42.57	25.94**	19.57*	-11.01	34.25	-5.94	-11.65	-1.96	38.41	9.41	8.55	-7.19
IS 10305 X IS 2263	28.27	-18.42**	-20.60**	-40.91**	31.13	1.48	-8.58	-10.88	29.70	-9.07	-14.72	-28.23**
IS 10305 X IS 13211	33.03	0.56	-1.98	-30.94**	27.85	-15.69*	-28.16**	-20.28**	30.44	-7.59	-13.97	-26.44**
SPV 1359 X IS 2263	31.23	-3.45	-12.27	-34.70**	31.55	0.65	-7.36	-9.69	31.39	-1.44	-9.87	-24.15**
SPV 1359 X IS 13211	34.47	12.82	7.71	-27.94**	26.92	-20.13**	-30.57**	-22.95**	30.70	-4.44	-13.24	-25.82**
SPV 1359 X IS 10305	33.07	5.31	-1.88	-30.87**	27.82	-0.54	-2.85	-20.37**	30.45	2.58	-0.16	-26.42**
C.D. (5%)		4.64	5.38	5.28		4.50	5.19	5.19		4.50	5.19	5.19
C.D. (1%)		6.24	7.23	7.23		6.05	6.98	6.98		5.97	6.90	6.90

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

the seasons. Highest negative significant heterosis was exhibited by IS 10305 X IS 13211, IS 2263 X IS 13211 and SPV 1359 X IS 2263 in 2010, 2011 and across the seasons, respectively, while lowest heterosis was recorded by IS 10305 X IS 13211, IS 2263 X IS 13211 and SPV 1359 X IS 2263 in 2010, 2011 and across the seasons, respectively.

Heterosis over standard check varied from -18.92 % (IS 10305 X IS 13211) to 102.70 % (IS 2263 X SPV 1359) in 2010, from 30.56 % (IS 10305 X IS 13211) to 116.67 % (SPV 1359 X IS 13211) in 2011 and from 12.95 % (SPV 1359 X IS 2263) to 108.12 % (IS 2263 X SPV 1359) across the seasons. All crosses exhibited significant positive heterosis over standard check in both the seasons and across the seasons except IS 10305 X IS 13211 in 2010 and SPV 1359 X IS 2263 across the seasons. Highest standard heterosis was recorded by IS 2263 X SPV 1359 in 2010 and across the seasons, SPV 1359 X IS 13211 in 2011, while lowest heterosis was exhibited by IS 10305 X IS 13211 in both the seasons and SPV 1359 X IS 2263 across the seasons over the check because of its shortest stature among all the crosses.

Most of the crosses were positively heterotic over standard check across the seasons. The crosses which showed significant positive heterosis over mid-parent also recorded significant positive heterosis over better parent. Similar results were reported by Bhagmal and Mishra (1985), Berenji (1988), Chinna and Phul (1988), Choudhari (1992) and Biradar (1995). Heterosis over better parent in positive direction was observed by Senthil and Palaniswamy (1993), Ganesh *et al.* (1996), Lokapur (1997) and Pawar (2000), while Patel *et al.* (1987), Desai (1991) and Belavatagi (1997) noticed significant positive heterosis over commercial check. Shivanna (1989) reported positive as well as negative heterosis in different crosses. Contrarily, Patel *et al.* (1990) observed negative heterosis for this trait.

4.1.2.2 Days to 50 % Flowering: Negative heterosis for days to 50 % flowering is an indication of earliness of a hybrid. Early maturing hybrids are desirable as they produce more yields per day and fit well in multiple cropping systems. Heterosis over mid-parent varied from -5.73 % (IS 2263 X IS 10305) to 19.74 % (IS 13211 X SPV 1359) in 2010, from -24.74 % (IS 13211 X IS 2263) to -1.09 % (SPV 1359 X IS 2263) in 2011 and from 6.87 % (IS 2263 X IS 13211) to 10.62 % (IS 13211 X SPV 1359) across the seasons. Three crosses (IS 13211 X SPV 1359, IS 10305 X IS 13211 and IS 10305 X IS 2263) recorded significant positive heterosis over mid-parent in 2010, while none of the crosses were positively heterotic over mid-parent in 2011. Across the seasons, IS 13211

X SPV 1359 showed maximum significant positive heterosis over mid-parent. Most of the crosses were negatively heterotic across the seasons. Six crosses recorded negative heterosis for days to 50 % flowering consistently in both the seasons. Highest negative heterosis was recorded by IS 2263 X IS 10305, IS 13211 X IS 2263 and IS 2263 X IS 13211 in 2010, 2011 and across the seasons, respectively. Highestpositive heterosis was exhibited by IS 13211 X SPV 1359 in 2010 and across the seasons.

The range of heterosis over better parent was observed to be from -5.31 % (IS 2263 X IS 10305) to 21.24 % (IS 10305 X IS 13211) in 2010, from -21.98 % (IS 13211 X IS 2263) to 10.11 % (IS 2263 X IS 10305) in 2011 and from -5.25 % (IS 2263 X IS 13211) to 11.91 % (IS 13211 X SPV 1359) across the seasons. One cross (IS 2263 X IS 10305) in 2010, four crosses (IS 13211 X IS 2263, IS 2263 X IS 13211, IS 13211 X SPV 1359 and IS 13211 X IS 10305) in 2011 and two crosses (IS 2263 X IS 13211and IS 13211 X IS 2263) across the seasons recorded negative significant heterosis over better parent, which are desirable to attain early maturity, while four crosses (IS 10305 X IS 13211, IS 13211 X SPV 1359, IS 10305 X IS 2263 and IS 13211 X IS 2263) in 2010, one cross (IS 2263 X IS 10305) in 2011 and three crosses (IS 13211 X SPV 1359, SPV 1359 X IS 2263 and IS 10305 X IS 13211) across the seasons showed significant positive heterosis. Highly negative heterotic crosses were IS 2263 X IS 10305, IS 13211 X IS 2263 and IS 2263 X IS 13211 in 2010, 2011 and across the seasons, respectively.

Heterosis over standard check ranged from 2.88 % (IS 2263 X IS 10305) to 34.13 % (IS 13211 X SPV 1359) in 2010, from -5.62 % (IS 13211 X IS 10305) to 29.78 % (SPV 1359 X IS 13211) in 2011 and from 5.54 % (IS 13211 X IS 10305) to 29.15 % (IS 13211 X SPV 1359) across the seasons. None of the crosses recorded significant negative heterosis over standard check in individual seasons and across the seasons indicating that all the crosses were either on par or late in maturity when compared to check. However, IS 13211 X IS 10305 showed negative but non-significant heterosis in 2011, since this cross flowered earlier than the check during that season. All crosses showed significant positive heterosis over check in 2010 and across the seasons. Seven crosses exhibited significant positive heterosis over check in 2011. IS 13211 X SPV 1359 in 2010 and across the seasons and SPV 1359 X IS 13211 in 2011 were highly heterotic crosses over standard check which might be due to the involvement of both late maturing parents in the development of these crosses.

Most of the hybrids showed negative heterosis over mid-parent and better parent in both the seasons and across the seasons. Naik *et al.* (1994), Lokapur (1997) and Pawar (2000) also reported the similar results, while Kanaka (1979), Atkins (1979), Rao *et al.* (1993), Biradar (1995) and Ganesh *et al.* (1996) noticed that hybrids recorded positive heterosis over better parent. However, Indi and Goud (1981), Desai *et al.* (1985), Kide *et al.* (1985), Shivanna and Patil (1988) and Belavatagi (1997) obtained positive heterosis over mid-parent and Rao *et al.* (1976), Pandit (1989), Senthil and Palaniswamy (1993), Badhe and Patil (1997) and Tiwari *et al.* (2003) documented positive heterosis over better parent. Since, check was earlier to flower than all the crosses, all crosses recorded positive heterosis over standard check. IS 2263 X IS 10305, IS 13211 X IS 2263 and IS 2263 X IS 13211 showed highest negative heterosis over both mid-parent and better parent in 2010, 2011 and across the seasons, respectively.

4.1.2.3 100-Grain Weight (g): Heterosis over mid-parent ranged from -15.65 % (IS 10305 X IS 13211) to 25.40 % (SPV 1359 X IS 10305) in 2010, from -6.89 % (IS 2263 X IS 13211) to 24.68 % (IS 10305 X IS 2263) in 2011 and from -44.15 % (SPV 1359 X IS 2263) to 67.43 % (IS 10305 X IS 13211) across the seasons. Two crosses (SPV 1359 X IS 10305 and IS 2263 X IS 10305) in 2010 and six crosses (IS 10305 X IS 2263, SPV 1359 X IS 13211, IS 13211 X IS 10305, IS10305 X SPV 1359, SPV 1359 X IS 10305 and IS 13211 X SPV 1359) in 2011 recorded significant positive heterosis. More than 50 per cent of the crosses exhibited significant positive heterosis across the seasons. Highly heterotic crosses for 100-grain weight were SPV 1359 X IS 10305, IS 10305 X IS 2263 and IS 10305 X IS 13211 in 2010, 2011 and across the seasons, respectively.

Heterosis over better parent varied from -29.25 % (IS 10305 X IS 13211) to 1.03 % (IS 2263 X IS 13211) in 2010, from -23.38 % (IS 2263 X IS 13211) to 16.67 % (IS 13211 X IS 10305) in 2011 and from -48.27 % (SPV 1359 X IS 2263) to 50.41 % (IS 10305 X IS 13211) across the seasons. None of the crosses recorded significant positive heterosis over better parent in both the seasons except IS 13211 X IS 10305 in 2011 and IS 10305 X IS 13211 across the seasons. Three crosses (IS 10305 X IS 13211, IS 13211 X SPV 1359 and IS 10305 X SPV 1359) in 2010, five crosses (IS 2263 X IS 13211, SPV 1359 X IS 10305, IS 13211 X SPV 1359, IS 2263 X IS 10305 and IS 10305 X SPV 1359) in 2011 and three crosses (SPV 1359 X IS 2263, IS 13211 X SPV 1359 and IS 10305 X SPV 1359) across the seasons recorded significant negative heterosis over better parent. IS 2263 X IS 13211, IS 13211 X IS 10305 and IS 10305 X IS 13211 were crosses with highest heterosis over better parent in 2010, 2011 and across the seasons, respectively.

Heterosis over standard check ranged from -40.48 % (IS 10305 X IS 13211) to 16.30 % (SPV 1359 X IS 13211) in 2010, from -27.71 % (IS 10305 X IS 13211) to 26.26 % (SPV 1359 X IS 13211) in 2011 and from -34.29 % (SPV 1359 X IS 2263) to 21.13 % (SPV 1359 X IS 13211). None of the crosses in 2010 had significant positive heterosis, while seven crosses (SPV 1359 X IS 13211, SPV 1359 X IS 2263, IS 2263 X SPV 1359, IS 10305 X SPV 1359, IS 10305 X IS 2263, IS 13211 X SPV 1359 and SPV 1359 X IS 10305) in 2011 and three crosses (SPV 1359 X IS 13211, IS 10305 X IS 13211 and IS 2263 X SPV 1359) across the seasons recorded significant positive heterosis over standard check. Significant negative heterosis was exhibited by IS 10305 X IS 13211 in 2010, IS 10305 X IS 13211 and its reciprocal cross in 2011 and SPV 1359 X IS 2263 across the seasons. Highest and lowest heterosis were recorded by SPV 1359 X IS 13211 and IS 10305 X IS 13211 in both the seasons, respectively due to the highest and lowest *per se* performance of the female parents *viz.*, SPV 1359 and IS 10305 involved in the development of these crosses.

Nearly 50 % of the hybrids showed heterosis over both the parents for 100-grain weight. This result was in concordance with the reports of Shivanna (1989), Rao *et al.* (1993) and Biradar (1995) who noticed limited heterosis for this trait. Contrarily, a wide range of heterosis was reported by Rao (1970), Kanaka (1979), Desai *et al.* (1980), Desai *et al.* (1983), Shinde *et al.* (1983), Dinakar (1985) and Cabera and Miller (1985) for this trait. Only three crosses (IS 2263 X SPV 1359, IS 10305 X IS 13211 and SPV 1359 X IS 13211) were positively heterotic over check across the seasons and hence these crosses could be utilized to further improve the grain weight. Ganesh *et al.* (1996) also documented significant heterosis over check for this trait. However, these crosses were not positively heterotic over their respective better parents in both the seasons. Desai *et al.* (1985) also reported negative heterosis over the better parent for grain mass.

4.1.2.4 Grain Yield (t ha^{-1}): Heterosis over mid-parent for grain yield ranged from -23.65 % (IS 13211 X SPV 1359) to 152.90 % (IS 2263 X IS 10305) in 2010, from -24.61 % (IS 2263 X IS 13211) to 56.39 % (IS 13211 X IS 10305) in 2011 and from -16.24 % (IS 13211 X SPV 1359) to 86.29 % (IS 2263 X IS 10305) across the seasons. Five crosses (IS 2263 X IS 10305, IS 13211 X IS 10305, IS 10305 X SPV 1359, IS 10305 X IS 2263 and SPV 1359 X IS 10305) recorded highly significant positive heterosis over mid-parent in 2010 and across the seasons, while only one cross (SPV 1359 X IS 13211) recorded highly significant positive heterosis in 2011 and significant positive heterosis across the seasons. Only one cross (IS 13211 X SPV 1359) recorded highly significant negative heterosis in 2010. Highest heterosis was obtained with IS 2263 X IS 10305 in 2010 and across the seasons and IS 13211 X IS 10305 in 2011.

Heterosis over better parent varied from -43.42 % (IS 13211 X SPV 1359) to 48.26 % (IS 2263 X IS 10305) in 2010, from -57.23 % (IS 2263 X IS 13211 and IS 13211 X IS 2263) to 23.10 % (IS 13211 X IS 10305) in 2011 and from -44.31 % (IS 13211 X SPV 1359) to 33.50 % (IS 13211 X IS 10305) across the seasons. None of the crosses exhibited significant positive heterosis over better parent in both the seasons. Most of the crosses involving high yielders *i.e.*, either SPV 1359 or IS 2263 as one of the parents recorded significant negative heterosis over better parent. Highly heterotic crosses were IS 2263 X IS 10305 in 2010 and across the seasons and IS 13211 X IS 10305 in 2011.

Heterosis over standard check ranged from -17.27 % (IS 10305 X IS 13211) to 134.10 % (IS 10305 X SPV 1359) in 2010, from -49.49 % (IS 10305 X IS 13211) to 159.39 % (SPV 1359 X IS 2263) in 2011 and from -29.90 % (IS 10305 X IS 13211) to 130.37 % (SPV 1359 X IS 2263) across the seasons. All the crosses except IS 13211 X SPV 1359 and IS 10305 X IS 13211 had significant positive heterosis over standard check in 2010, while 50 % of the hybrids showed significant positive heterosis over standard check in 2011. However, only one cross, IS 10305 X IS 13211 showed significant negative heterosis in 2011. IS 10305 X SPV 1359 in 2010 and SPV 1359 X IS 2263 in 2011 and across the seasons were highly superior in grain yield compared to check.

The hybrids which showed significant positive heterosis over mid-parent also exhibited significant positive heterosis over standard check. Many earlier researchers also recorded significantly greater magnitude of heterosis for grain yield in sorghum (Indi and Goud, 1981 and Karthik, 2004). IS 2263 X IS 13211 and its reciprocal cross recorded similar *per se* performance for grain yield in 2011, suggesting the absence of maternal effect for this cross combination during that season.

4.1.2.5 Grain Iron (mg kg^{-1}): Heterosis over mid-parent for grain iron content ranged from -18.42 % (IS 10305 X IS 2263) to 34.86 % (IS 13211 X IS 10305) in 2010, from -20.13 % (SPV 1359 X IS 13211) to 10.09 % (IS 13211 X SPV 1359) in 2011 and from -9.07 % (IS 10305 X IS 2263) to 12.89 % (IS 13211 X SPV 1359) across the seasons. Five crosses (IS 13211 X IS 10305, IS 2263 X SPV 1359, IS 13211 X IS 2263, IS 13211 X SPV 1359 and IS 2263 X IS 13211) recorded significant positive heterosis over mid-parent in 2010, while none of the crosses exhibited significant positive heterosis in 2011 and across the seasons. However, IS 10305 X IS 2263 in 2010 and SPV 1359 X IS 13211, IS 13211 X IS 10305 and IS 10305 X IS 13211 in 2011 recorded significant negative heterosis over mid-parent. Highly heterotic crosses were IS 13211 X IS 10305 in 2010 and IS 13211 X SPV 1359 in 2011 and across the seasons.

Heterosis over better parent varied from -20.60 % (IS 10305 X IS 2263) to 31.45 % (IS 13211 X IS 10305) in 2010, from -30.57 % (SPV 1359 X IS 13211) to -1.16 % (IS 10305 X SPV 1359) in 2011 and from -14.72 % (IS 10305 X IS 2263) to 8.55 % (IS 13211 X IS 2263) across the seasons. Three crosses (IS 13211 X IS 10305, IS 13211 X IS 2263 and IS 2263 X SPV 1359) recorded significant positive heterosis over better parent in 2010. None of the crosses exhibited significant positive heterosis in 2011 and across the seasons. IS 10305 X IS 2263 in 2010 and SPV 1359 X IS 13211, IS 13211 X IS 10305, IS 10305 X IS 13211 and IS 2263 X SPV 1359 exhibited significant negative heterosis over better parent in 2011. Superior crosses over better parent were IS 13211 X IS 10305 in 2010 and IS 13211 X IS 2263 in 2011 and across the seasons (Fig 4.2).

Heterosis over standard check ranged from -40.91 % (IS 10305 X IS 2263) to -7.39 % (IS 13211 X IS 10305) in 2010, from -22.95 % (SPV 1359 X IS 13211) to 6.20 % (IS 13211 X SPV 1359) in 2011 and from -30.57 % (IS 10305 X SPV 1359) to -7.19 % (IS 13211 X IS 2263) across the seasons. Almost all the crosses recorded negative heterosis over standard check in both the seasons. However, the cross IS 13211 X SPV 1359 exhibited positive but non-significant heterosis in 2011. IS 2263 X SPV 1359, IS 10305 X SPV 1359, IS 10305 X IS 13211, SPV 1359 X IS 13211 and SPV 1359 X IS 10305 recorded significant negative heterosis consistently in both the seasons. However, IS 13211 X IS 2263 (-7.19 %), IS 2263 X IS 13211 (-12.36 %) and IS 13211 X SPV 1359 (-12.37 %) exhibited negative but non-significant heterosis across the seasons (Fig 4.3).

None of the crosses recorded significant positive heterosis over mid-parent, better parent and standard check across the seasons. These results indicated that there would be little opportunity to exploit heterosis for improving grain iron content in sorghum. Negative heterosis for grain iron was reported earlier in pearl millet by Velu (2006) and Rai *et al*. (2007) and in maize by Chakraborti *et al*. (2009).

4.1.3 Combining Ability Analysis

Combining ability analysis gives the information about the general combining ability of parents and specific combining ability of hybrids, which is useful for the selection of desirable parents for hybridization programme. It gives an indication of the

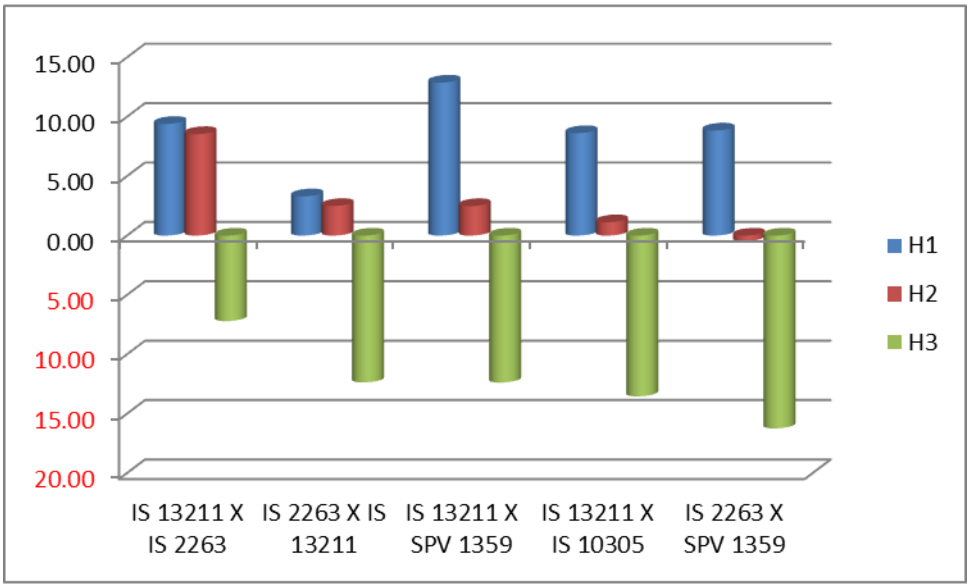

Figure 4.2. Heterosis over mid-parent, better parent and standard check exhibited by promising hybrids for grain iron across the seasons

H1: Heterosis over mid-parent; **H2: Heterosis over better parent;**
H3: Heterosis over standard check

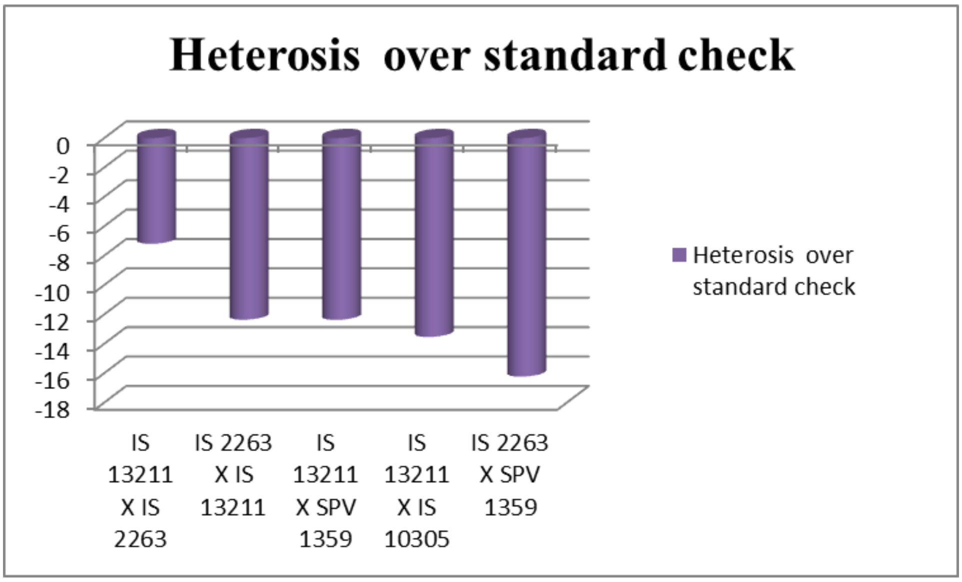

Figure 4.3. Heterosis over standard check exhibited by promising hybrids for grain iron across the seasons

variation due to GCA and SCA, which represents a relative measure of additive and non-additive gene actions, respectively. It is an established fact that dominance is a component of non-additive genetic variance (breeding value). Breeders use these variance components to infer the gene action and to assess the genetic potentialities of the parents in combination. The ultimate choice of parents to be used in a breeding programme is determined by *per se* performance and their behaviour in hybrid combination. It is therefore, necessary to assess the genetic potentialities of the parents in hybrid combination through systematic studies in relation to general and specific combining abilities. Generally diallel and line x tester mating designs are employed to generate the material necessary for the estimation of combining ability effects, which provide the basic idea about the genetic potential of parents. Diallel mating design was used in the present study for estimating combining abilities.

4.1.3.1 Analysis of Variance for Combining Ability: The analysis of variance for combining ability (Table 4.12. and 4.13.) revealed that the mean sum of squares due to GCA of parents was significant for all the characters in both the seasons. The mean sum of squares due to SCA was non-significant for plant height and 100-grain weight in 2010 and for grain yield in 2011. The mean sum of squares due to reciprocal crosses was significant for all the traits in both the seasons except grain yield in 2011.

The pooled analysis of variance (Table 4.14.) across the seasons for combining ability indicated that the mean sum of squares due to GCA, SCA and reciprocal crosses were highly significant for all the traits except the mean sum of squares due to SCA for grain iron.

The variance due to SCA was more than the variance due to GCA for days to 50 % flowering in both the seasons and grain yield and grain iron content in 2010, indicating the predominance of non-additive gene action in controlling the expression of these traits.

4.1.3.2. Gene Action and *gca, sca* and Reciprocal Effects: The gene action for various quantitative traits and their *gca, sca* and reciprocal effects are presented in Tables 4.15. and 4.16. and are discussed hereunder.

4.1.3.2.1 Plant Height: Plant height significantly varied among parents, direct crosses and reciprocal crosses in both the seasons and across the seasons. However, there was no significant variation among the direct crosses in *postrainy* season, 2010. For plant height, GCA variance was higher than the SCA variance in 2010 and across the seasons, suggesting the operation of additive gene action in controlling this trait. Further, predictability ratio (0.74) obtained for this trait revealed the predominant role of

Table 4.12. Analysis of variance for combining ability estimates for various agronomic characters and grain iron content in sorghum during *postrainy* season, 2010

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain iron (mg Kg^{-1})
GCA	3	0.64**	36.56**	1.37**	8.03**	24.91**
SCA	6	0.05	18.57**	0.06	2.85**	18.48**
Reciprocal	6	0.12**	43.99**	0.17 **	0.80**	26.54**
Error	30	0.02	0.39	0.04	0.12	3.56
GCA variance		0.08	4.52	0.17	0.99	2.67
SCA variance		0.02	18.18	0.02	2.73	14.92
GCA/ SCA		4	0.25	8.5	0.36	0.18
Predictability ratio		0.89	0.33	0.94	0.42	0.26

* indicates significance @ 5 % level of probability;

** indicates significance @ 1 % level of probability

Table 4.13. Analysis of variance for combining ability estimates for various agronomic characters and grain iron content in sorghum during *postrainy* season, 2011

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain iron (mg Kg^{-1})
GCA	3	0.82**	111.37**	1.52**	10.21**	37.51**
SCA	6	0.12**	84.44**	0.11**	0.23	7.02
Reciprocal	6	0.02**	13.61**	0.06*	0.18	9.79*
Error	30	0.01	3.63	0.02	0.11	3.41
GCA variance		0.1	13.47	0.19	1.26	4.26
SCA variance		0.11	80.81	0.09	0.12	3.61
GCA/ SCA		0.91	0.17	2.11	10.5	1.18
Predictability ratio		0.65	0.25	0.81	0.95	0.70

* indicates significance @ 5 % level of probability;

** indicates significance @ 1 % level of probability

Table 4.14. Pooled analysis of variance for combining ability estimates for various agronomic characters and grain iron content in sorghum

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain iron (mg Kg^{-1})
GCA	3	48.82**	22.86**	2.83**	17.80**	58.87**
SCA	6	4.45**	7.57**	0.14**	1.58**	2.98
Reciprocal	6	2.19**	16.29**	0.13**	0.83**	15.45**
Error	60	0.17	0.17	0.01	0.06	1.74
GCA variance		6.08	2.84	0.35	2.22	7.14
SCA variance		4.28	7.4	0.13	1.52	1.24
GCA/ SCA		1.42	0.38	2.69	1.46	5.76
Predictability ratio		0.74	0.43	0.84	0.74	0.92

* indicates significance @ 5 % level of probability;

** indicates significance @ 1 % level of probability

Table 4.15. Estimates of general and specific combining ability effects for plant height, days to 50 % flowering and 100-grain weight in sorghum in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Plant height (m)			Days to 50 % flowering			100 grain weight (g)		
	2010	2011	POOLED	2010	2011	POOLED	2010	2011	POOLED
***gca* effects**									
IS 2263	0.10*	0.08**	0.48**	-2.35**	1.42*	-0.87**	0.20**	0.18**	0.19**
IS 13211	-0.15**	-0.20**	-1.02**	2.65**	-0.25	1.19**	-0.22**	-0.37**	-0.29**
IS 10305	-0.30**	-0.30**	-1.70**	-0.90**	-5.00**	-1.17**	-0.45**	-0.34**	-0.40**
SPV 1359	0.35**	0.42**	2.24**	0.60**	3.83**	0.86**	0.47**	0.53**	0.50**
S.E (parents)	0.05	0.02	0.09	0.19	0.58	0.09	0.06	0.04	0.03
***sca* effects**									
IS 2263 X IS 13211	-0.05	-0.14**	-0.63**	-1.52**	-9.04**	-2.07**	0.06	-0.07	-0.00
IS 2263 X IS 10305	0.12	0.09*	0.58**	-0.48	1.54	0.01	0.20	0.28**	0.24**
IS 2263 X SPV 1359	0.02	0.01	0.08	-0.48	1.54	0.01	-0.06	-0.17*	-0.12*
IS 13211 X IS 10305	-0.05	0.09*	0.21	3.35**	-5.29**	0.75**	-0.09	-0.05	-0.07
IS 13211 X SPV 1359	-0.13	0.24**	0.62**	4.02**	-0.63	1.77**	-0.04	0.29**	0.12**
IS 10305 X SPV 1359	0.19*	0.24**	1.24**	-1.77**	-0.38	-0.88**	0.20	0.14	0.17**
S.E (Direct crosses)	0.08	0.04	0.16	0.35	1.06	0.16	0.11	0.08	0.05

Table 4.15. (Contd.)

Genotype	Plant height (m)			Days to 50 % flowering			100 grain weight (g)		
	2010	2011	POOLED	2010	2011	POOLED	2010	2011	POOLED
Reciprocal effects									
IS 13211 X IS 2263	-0.02	-0.12*	-0.47*	-1.00*	0.33	-0.41*	0.19	-0.24*	-0.03
IS 10305 X IS 2263	0.13	-0.12*	-0.17	-3.17**	2.50	-1.09**	0.16	-0.19*	-0.01
IS 10305 X IS 13211	0.42**	0.03	0.94**	-8.00**	-2.00	-4.00**	0.39**	0.22*	0.30**
SPV 1359 X IS 2263	0.12	0.02	0.29	0.67	-0.33	0.26	0.03	-0.07	-0.02
SPV 1359 X IS 13211	-0.25*	-0.13*	-0.99**	7.50**	-5.50**	2.64**	-0.44**	-0.18	-0.31**
SPV 1359 X IS 10305	-0.28**	-0.13*	-1.05**	-0.50	0.33	-0.18	-0.31*	0.10	-0.11
S.E (Reciprocal crosses)	0.1	0.05	0.20	0.44	1.35	0.20	0.13	0.10	0.06

* indicates significance @ 5 % level of probability; ** indicates significance @ 1 % level of probability

Table 4.16. Estimates of general and specific combining ability effects for grain yield and grain iron in sorghum in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Grain yield (t ha^{-1})			Grain iron (mg kg^{-1})		
	2010	2011	POOLED	2010	2011	POOLED
***gca* effects**						
IS 2263	0.18	0.66**	0.42**	1.27*	1.40*	1.34**
IS 13211	-0.82**	-1.13**	-0.97**	1.69**	2.22**	1.96**
IS 10305	-0.71**	-0.76**	-0.74**	-0.98	-2.35**	-1.66**
SPV 1359	1.34**	1.24**	1.29**	-1.98**	-1.28*	-1.63**
S.E (parents)	0.11	0.1	0.05	0.58	0.57	0.29
***sca* effects**						
IS 2263 X IS 13211	0.37	-0.53**	-0.08	2.74**	-0.39	1.17*
IS 2263 X IS 10305	1.11**	0.30	0.70**	-3.14**	1.31	-0.91
IS 2263 X SPV 1359	-0.51**	0.09	-0.21*	2.18*	-1.27	0.45
IS 13211 X IS 10305	-0.02	0.15	0.07	3.10**	-3.21**	-0.05
IS 13211 X SPV 1359	-0.53**	0.39*	-0.07	0.39	0.17	0.28
IS 10305 X SPV 1359	1.57**	-0.13	0.72**	-0.77	0.80	0.01
S.E (Direct crosses)	0.19	0.18	0.09	1.05	1.03	0.52
Reciprocal effects						
IS 13211 X IS 2263	0.04	-0.00	0.02	-2.02	-0.13	-1.07
IS 10305 X IS 2263	0.85**	0.26	0.56**	3.73**	0.13	1.93**
IS 10305 X IS 13211	0.76**	0.13	0.44**	5.63**	-0.29	2.67**
SPV 1359 X IS 2263	-0.58*	-0.22	-0.40**	5.08**	-1.81	1.64*
SPV 1359 X IS 13211	-0.87**	-0.64**	-0.76**	0.48	5.09**	2.79**
SPV 1359 X IS 10305	0.08	0.03	0.06	-1.95	0.24	-0.85
S.E (Reciprocal crosses)	0.24	0.23	0.12	1.33	1.31	0.66

additive gene action. The present results are in line with the earlier reports of Borikar and Bhale (1982), Nayakar (1985), Chandrashekharappa (1987), Shivanna and Patil (1988), Sakhare *et al.* (1992), Shivanna *et al.* (1992) and Senthil and Palaniswamy (1994). Contrarily, the importance of non-additive gene action with pronounced SCA variance was reported by Berenji (1988), Iyanar *et al*. (2001) and Umakanth *et al.* (2002). The variances due to both GCA and SCA were almost similar in 2011, indicating the influence of both additive and non-additive gene actions on this trait which was in agreement with the reports of Rao and Goud (1977), Giriraj and Goud (1983), Dabholkar and Lal (1987), Dinakar (1985), Sahib and Reddy (1986) and Chand (1996) for this character.

The general combining ability (*gca*) effects for plant height ranged from -0.30 (IS 10305) to 0.35 (SPV 1359) in 2010, from -0.30 (IS 10305) to 0.42 (SPV 1359) in 2011 and from -1.70 (IS 10305) to 2.24 (SPV 1359) across the seasons. IS 10305 followed by IS 13211 exhibited significant negative *gca* effects in individual seasons and across the seasons and hence they can be used as parents (general combiners) in further crossing programmes if short stature is desirable, while SPV 1359 followed by IS 2263 exhibited significant positive *gca* effects in both the seasons and across the seasons and hence they can be used as parents for fodder improvement programmes. Thorough observation of the *per se* performance of plant height with *gca* effects in 2010, 2011 and across the seasons clearly indicated that the parents with tall stature (SPV 1359 and IS 2263) recorded significant positive *gca* effects, whereas parents with short stature (IS 10305 and IS 13211) exhibited significant negative *gca* effects.

The *sca* effects for plant height ranged from -0.13 (IS 13211 X SPV 1359) to 0.19 (IS 10305 X SPV 1359) in 2010, from -0.14 (IS 2263 X IS 13211) to 0.24 (IS 13211 X SPV 1359 and IS 10305 X SPV 1359) in 2011 and from -0.63 (IS 2263 X IS 13211) to 1.24 (IS 10305 X SPV 1359) across the seasons. IS 10305 X SPV 1359 followed by IS 2263 X IS 10305 in 2010, IS 13211 X SPV 1359 and IS 10305 X SPV 1359 in 2011 and IS 10305 X SPV 1359 followed by IS 13211 X SPV 1359 across the seasons recorded highest positive *sca* effects, while IS 13211 X SPV 1359 in 2010 and IS 2263 X IS 13211 in 2011 and across the seasons exhibited highest negative *sca* effects. IS 2263 X IS 10305, IS 13211 X SPV 1359 and IS 10305 X SPV 1359 recorded significant positive *sca* effects consistently in 2011 and across the seasons. In addition to these crosses, IS 10305 X SPV 1359 and IS 13211 X IS 10305 showed significant positive *sca* effects in 2010 and 2011, respectively. Among these hybrids, IS 2263 X IS 10305, IS 13211 X SPV 1359 and IS 10305 X SPV 1359 had one of their parents as good general combiner and other parent as poor combiner for tallness. Involvement of at least one parent with high *gca* effects indicated that a good general combiner in the cross combination might result in good specific combinations. Peng and Virmani (1990) also reported the possibility of interaction between positive alleles from good combiner and negative alleles from poor combiner in good x poor combiner crosses and suggested for exploitation of heterosis in F_1 generation. One cross, IS 2263 X IS 13211 recorded significant negative *sca* effects in 2011 and across the seasons, which had a good general combiner as one of the parents and a poor combiner as the other parent. This cross can be used to further reduce the plant height, wherever mechanical harvesting is to be done.

Reciprocal effects varied from -0.28 (SPV 1359 X IS 10305) to 0.42 (IS 10305 X IS 13211) in 2010, from -0.13 (SPV 1359 X IS 13211 and SPV 1359 X IS 10305) to 0.03 (IS 10305 X IS 13211) in 2011 and from -1.05 (SPV 1359 X IS 10305) to 0.94 (IS 10305 X IS 13211) across the seasons. IS 10305 X IS 13211 followed by IS 10305 X IS 2263 in 2010 and IS 10305 X IS 13211 followed by SPV 1359 X IS 2263 in 2011 and across the seasons exhibited highest positive reciprocal effect, while SPV 1359 X IS 10305 recorded highest negative reciprocal effect consistently in both the seasons and across the seasons. IS 10305 X SPV 1359 was identified to be the best cross with the highest positive *sca* effect across the seasons for plant height involving a good general combiner as one of the parents and a poor combiner as the other parent. SPV 1359 X IS 13211 and SPV 1359 X IS 10305 recorded significant negative *sca* effects consistently in individual seasons and across the seasons. Besides these crosses, IS 13211 X IS 2263 in 2011 and across the seasons and IS 10305 X IS 2263 in 2011 recorded significant negative *sca* effects. IS 10305 X SPV 1359 and its reciprocal cross showed very high significant variation for plant height, suggesting possible role of maternal effect in controlling this trait. It is noticed from the above results that there is no clear cut relationship between *gca* effects of the parents and *sca* effects of the hybrids at least in the material used in this study. As the additive gene action was predominant, hybridization followed by simple selection through pedigree method of breeding might be useful for the improvement of this trait.

4.1.3.2.2 Days to 50 % Flowering: The character, days to 50 % flowering varied significantly among the parents and crosses in individual seasons and across the seasons. Low ratio of GCA to SCA variances for days to 50 % flowering suggested that this trait is under the control of non-additive gene action in both the seasons and across the seasons. Predictability ratio (0.43) obtained for this trait further supported the role of non-additive gene action in controlling this character. These results are in conformity with the earlier reports of Kide *et al*. (1985), Shivanna (1989), Naik *et al.* (1994), Belavatagi (1997), Biradar (1995) and Kanawade *et al.* (2001). Contrarily, importance of additive gene action for days to 50% flowering was reported by Nayakar (1985), Dabholkar and Usha (1988), Shivanna *et al.* (1992), Senthil and Palaniswamy (1994) and Siddiqui and Baig (2001), while Kanaka (1979) and Patel *et al.* (1995) found the importance of both additive and non-additive components of genetic variances for days to 50 per cent flowering.

The negative estimates of *gca* and *sca* are considered to be favourable for days to 50 % flowering as they give rise to early duration hybrids. *gca* effects for days to 50 % flowering ranged from -2.35 (IS 2263) to 2.65 (IS 13211) in 2010, from -5.00 (IS 10305) to 3.83 (SPV 1359) in 2011 and from -1.17 (IS 10305) to 1.19 (IS 13211) across the seasons. IS 2263 followed by IS 10305 in 2010, IS 10305 followed by IS 13211 in 2011 and IS 10305 followed by IS 2263 across the seasons exhibited highest negative *gca* effects. Hence, they can be used as good general combiners to attain early maturity. Significant positive *gca* effects were recorded by IS 13211 followed by SPV 1359 in 2010 and across the seasons and SPV 1359 followed by IS 2263 in 2011.

The *sca* effects varied from -1.77 (IS 10305 X SPV 1359) to 4.02 (IS 13211 X SPV 1359) in 2010, from -9.04 (IS 2263 X IS 13211) to 1.54 (IS 2263 X IS 10305 and IS 2263 X SPV 1359) in 2011 and from -2.07 (IS 2263 X IS 13211) to 1.77 (IS 13211 X SPV 1359) across the seasons. IS 10305 X SPV 1359 followed by IS 2263 X IS 13211 in 2010, IS 2263 X IS 13211 followed by IS 13211 X IS 10305 in 2011 and IS 2263 X IS 13211 followed by IS 10305 X SPV 1359 across the seasons were the best crosses with early flowering with highest negative significant *sca* effects. All these crosses were the result of good x poor or poor x good combiners. Highest positive significant *sca* effects were recorded by IS 13211 X SPV 1359 followed by IS 13211 X IS 10305 in 2010 and across the seasons, while none of the crosses recorded significant positive *sca* effects in 2011. Due to seasonal effect, IS 13211 X IS 10305 recorded high positive significant *sca* effect and high negative significant *sca* effect in 2010 and 2011, respectively.

Reciprocal effects varied from -8.00 (IS 10305 X IS 13211) to 7.50 (SPV 1359 X IS 13211) in 2010, from -5.50 (SPV 1359 X IS 13211) to 2.50 (IS 10305 X IS 2263) in 2011 and from -4.00 (IS 10305 X IS 13211) to 2.64 (SPV 1359 X IS 13211) across the seasons. IS 10305 X IS 13211 followed by IS 10305 X IS 2263 in

2010 and across the seasons and SPV 1359 X IS13211 in 2011 were desirable crosses with highest significant negative reciprocal effects. In addition to these crosses, IS 13211 X IS 2263 exhibited significant negative reciprocal effect in 2010 and across the seasons. There was no significant variation between the direct crosses and reciprocal crosses for days to 50 % flowering. IS 10305 X IS 13211 was found to be the early cross among all the crosses with the highest negative *sca* effects which involved the parents with good x poor general combiners suggesting the existence of genetic diversity in the form of a number of heterozygous loci in both the parents. Since, this trait was governed by non-additive gene action, pedigree and bulk method with recurrent selection or diallel selective or through exploitation of heterosis breeding can be followed to further improve the earliness of the hybrids.

4.1.3.2.3 100-Grain Weight (g): Test weight (100-grain weight) is an important component character of grain yield. 100-grain weight significantly varied among all the parents and crosses in individual seasons and across the seasons. However, direct crosses did not reveal significant variation in 2010. The variance for combing ability indicated the greater GCA variance than the SCA variance pointing out the importance of additive gene action in the inheritance of this trait, since this trait was strongly supported by the higher value of predictability ratio. These results are in confirmity with the earlier reports of Nayakar (1985), Dabholkar and Usha (1988), Jagadishwar and Shinde (1992) and Shivanna *et al*. (1992). Negating the results obtained in the present study, non-additive gene action was reported by Patil and Thombre (1984), Shivanna (1989) and Patel *et al*. (1990).

For 100-grain weight, *gca* effects varied from -0.45 (IS 10305) to 0.47 (SPV 1359) in 2010, from -0.37 (IS 13211) to 0.53 (SPV 1359) in 2011 and from -0.40 (IS 10305) to 0.50 (SPV 1359) across the seasons. Among the parents, SPV 1359 followed by IS 2263 recorded significant positive *gca* effects, while IS 10305 followed by IS 13211 exhibited significant negative *gca* effects in 2010 and across the seasons.

For direct crosses, *sca* effects varied from -0.09 (IS 13211 X IS 10305) to 0.20 (IS 2263 X IS 10305 and IS 10305 X SPV 1359) in 2010, from -0.17 (IS 2263 X SPV 1359) to 0.29 (IS 13211 X SPV 1359) in 2011 and from -0.12 (IS 2263 X SPV 1359) to 0.24 (IS 2263 X IS 10305) across the seasons. None of the crosses showed significant *sca* effects in 2010. IS 13211 X IS 10305 recorded highest negative but non-significant *sca* effect in 2010. IS 2263 X IS 10305 and IS 10305 X SPV 1359 in 2010, IS 13211 X SPV 1359 followed by IS 2263 X IS 10305 in 2011 and IS 2263 X IS 10305 followed by IS 10305 X SPV 1359 across the seasons showed highest positive *sca* effects. In all these crosses, at least one parent had good general combining ability for this trait. One cross, IS 2263 X SPV 1359 recorded significant negative *sca* effect in 2011 and across the seasons. Even though, the cross recorded significant negative *sca* effect, both of its parents were with high positive significant *gca* effects. This might be due to the presence of genetic diversity in the form of a number of heterozygous loci in the parents as reported by Pathak *et al*. (1993). Gupta (1981) also observed that *gca* of the parents in general had no bearing on the *sca* effects of the cross *i.e*., the crosses involving parents with high *gca* recorded less *sca* effects, while the parents with poor *gca* effect exhibited high *sca* effects.

Reciprocal effects ranged from -0.44 (SPV 1359 X IS 13211) to 0.39 (IS 10305 X IS 13211) in 2010, from -0.24 (IS 13211 X IS 2263) to 0.22 (IS 10305 X IS 13211) in 2011 and from -0.31 (SPV 1359 X IS 13211) to 0.30 (IS 10305 X IS 13211) across the seasons. IS 10305 X IS 13211 recorded highest significant positive reciprocal effect consistently in both the seasons and across the seasons which could be ascribed to the involvement of good general combiners as parents. However, it did not show significant positive *sca* effect in reverse direction indicating the influence of maternal effect. SPV 1359 X IS 13211 in 2010, IS 13211 X IS 2263 in 2011 and SPV 1359 X IS 13211 across the seasons exhibited significant negative *sca* effects with a good general combiner as one of the parents indicating that both parents need not have high *gca* to explore good *sca*. Among all the crosses, IS 10305 X IS 13211 was identified to be the best cross with highest positive *sca* effects involving both the parents with poor combining ability. The superiority of poor x poor combinations might be due to concentration and interaction of favourable genes contributed by the parents. As additive gene action was found to play a major role in governing this trait, hybridization followed by simple selection through pedigree method of breeding may be followed to further improve the grain weight.

4.1.3.2.4 Grain Yield (t ha^{-1}): Grain yield is the most important trait which determines the worthiness of a hybrid. High grain yield forms the major objective in any plant breeding programme. Both parents and crosses varied significantly for grain yield in 2010 and across the seasons, while only parents varied significantly in 2011. GCA variance was lower than SCA variance in 2010, whereas in 2011 and across the seasons, SCA variance was lower than GCA variance. As a whole, grain yield was controlled by additive gene action, since predictability ratio obtained was closer to unity (0.74) across the seasons. Similar trend of results were reported by Palaniswamy and Subramanian (1986), Senthil and Palaniswamy (1994) and Iyanar *et al.* (2001), whereas Ross *et al.*

(1983), Dinakar (1985), Dabholkar and Usha (1988), Swarnalatha and Rana (1988), Patel *et al.* (1990), Jagadishwar and Shinde (1992), Sakhare *et al.* (1992), Shivanna *et al.* (1992), Rao *et al.* (1994) and Naik *et al.* (1994) opined that both GCA and SCA variances were important for grain yield. Yet, interestingly Rao and Goud (1977), Wilson *et al.* (1978), Patil and Thombre (1984), Kishan and Borikar (1988), Shivanna (1989), Armugam *et al.* (1995) and Siddiqui and Baig (2001) observed preponderance of non-additive gene action controlling grain yield. In this study, the magnitude of GCA variance was larger in proportion, which suggested the predominance of additive and additive x additive gene effects for this trait. A parent with high *per se* performance was mostly a good general combiner though it may not produce good specific combinations always. It was observed that at least one good general combining parent was involved in desirable specific combination. Similarly, a good combiner when included in hybrid combination as one of the parent, the resultant hybrid possessed mostly high *sca* effects (Ravindrababu *et al*. 2001).

Wide range of *gca* effects for grain yield from -0.82 (IS 13211) to 1.34 (SPV 1359) in 2010, from -1.13 (IS 13211) to 1.24 (SPV 1359) in 2011 and from -0.97 (IS 13211) to 1.29 (SPV 1359) across the seasons were obtained. Among the parents, SPV 1359 followed by IS 2263 and IS 13211 followed by IS 10305 recorded highest significant positive and negative *gca* effects, respectively in both the seasons and across the seasons. SPV 1359 could be considered as good general combiner among all the parents.

The *sca* effects varied from -0.53 (IS 13211 X SPV 1359) to 1.57 (IS 10305 X SPV 1359) in 2010, from -0.53 (IS 2263 X IS 13211) to 0.39 (IS 13211 X SPV 1359) in 2011 and from -0.21 (IS 2263 X SPV 1359) to 0.72 (IS 10305 X SPV 1359) across the seasons. Among the six direct crosses, IS 10305 X SPV 1359 followed by IS 2263 X IS 10305 exhibited highest significant positive *sca* effects in 2010 and across the seasons, while IS 13211 X SPV 1359 recorded significant positive *sca* effect in 2011. All these crosses had at least one parent with high *gca*.

The reciprocal effects ranged from -0.87 (SPV 1359 X IS 13211) to 0.85 (IS 10305 X IS 2263) in 2010, from -0.64 (SPV 1359 X IS 13211) to 0.26 (IS 10305 X IS 2263) in 2011 and from -0.76 (SPV 1359 X IS 13211) to 0.56 (IS 10305 X IS 2263) across the seasons. IS 10305 X IS 2263 followed by IS 10305 X IS 13211 recorded highest positive reciprocal effects across the seasons and hence, these are the best crosses with respect to yield. IS 10305 X IS 2263 possessed only one parent with good *gca*, while IS 10305 X IS 13211 had both of its parents with good *gca*. SPV 1359 X

IS 2263 in 2010 and across the seasons and SPV 1359 X IS 13211 in both the seasons and across the seasons recorded significant negative reciprocal effects. IS 10305 X SPV 1359 was found to be the superior cross with highest positive *sca* effects involving one parent with higher *gca* and the other with lower *gca*. This might be due to the possibility of interaction between positive alleles from good combiner and negative alleles from poor combiner in good x poor combiner crosses suggesting the possibility for exploitation of heterosis for improving the grain yield.

4.1.3.2.5 Grain Iron (mg kg^{-1}): Parents and reciprocal crosses varied significantly in individual seasons and across the seasons, while direct crosses had significant variation in 2010. GCA variance was significantly lower than SCA variance in 2010, whereas in 2011 and across the seasons, SCA variance was lower than GCA variance suggesting that grain iron was controlled by additive gene action across the seasons. Higher predictability ratio (0.92) obtained for grain iron strongly supports the role of additive gene action for this trait. This result was in conformity with the reports of Velu (2006), Velu *et al*. (2011), Long *et al*. (2004) and Chen *et al*. (2007), however contradictory results were obtained by Aruselvi *et al*. (2009) and Zhang *et al*. (1996).

Among the parents, *gca* effects ranged from -1.98 (SPV 1359) to 1.69 (IS 13211) in 2010, from -2.35 (IS 10305) to 2.22 (IS 13211) in 2011 and from -1.66 (IS 10305) to 1.96 (IS 13211) across the seasons. IS 13211 followed by IS 2263 recorded highest significant positive *gca* effects consistently in both the seasons and across the seasons and hence, those parents could be considered as best parents. SPV 1359 in 2010 and IS 10305 in 2011 and across the seasons recorded highest significant negative *gca* effects.

The *sca* effects varied from -3.14 (IS 2263 X IS 10305) to 3.10 (IS 13211 X IS 10305) in 2010, from -3.21 (IS 13211 X IS 10305) to 1.31 (IS 2263 X IS 10305) in 2011 and from -0.91 (IS 2263 X IS 10305) to 1.17 (IS 2263 X IS 13211) across the seasons. *sca* effects obtained in 2010 and 2011 indicated the role of seasonal influence on grain iron content. IS 13211 X IS 10305 followed by IS 2263 X IS 13211 in 2010, IS 2263 X IS 10305 followed by IS 10305 X SPV 1359 in 2011 and IS 2263 X IS 13211 followed by IS 2263 X SPV 1359 across the seasons recorded highest positive *sca* effects. All these crosses had one parent as good combiner. However, IS 2263 X IS 13211 was the resultant of a cross involving two good combiners as parents, whereas IS 10305 X SPV 1359 was obtained by involving both poor combiners as parents, suggesting that there was no correlation between *gca* effects and *sca* effects. Two poor combiners can also give rise to a hybrid with high positive *sca* effects which might be due to the better nicking ability of the parents. The poor general combiners tend to produce significant *sca* effects in the hybrids, wherein the parental combinations provided environment for full expression of genes controlling this trait, though the parents themselves could not express any superiority for this trait. Accumulation of favourable genes may be the cause of parents with poor *gca* giving rise to hybrids with higher *sca* effects. IS 2263 X IS 13211 in 2010 and across the seasons and IS 2263 X SPV 1359 and IS 13211 X IS 10305 in 2010 exhibited significant positive *sca* effects. Highest significant negative *sca* effect was shown by IS 2263 X IS 10305 and IS 13211 X IS 10305 in 2010 and 2011, respectively. None of the crosses showed negative significant *sca* effects across the seasons.

Reciprocal effects ranged from -2.02 (IS 13211 X IS 2263) to 5.63 (IS 10305 X IS 13211) in 2010, from -1.81 (SPV 1359 X IS 2263) to 5.09 (SPV 1359 X IS 13211) in 2011 and from -1.07 (IS 13211 X IS 2263) to 2.79 (SPV 1359 X IS 13211) across the seasons. IS 10305 X IS 13211 in 2010 and SPV 1359 X IS 13211 in 2011 and across the seasons recorded highest positive significant reciprocal effects and hence, could be considered as good specific combiners with one of their parents as good general combiner. SPV 1359 X IS 13211 had high grain iron and showed highest positive significant *sca* effects among all the crosses across the seasons (Fig 4.4). Though, it was the resultant of poor x good general combiner, the high performance of cross might be due to the interaction between positive alleles from good combiner and negative alleles from poor combiner. As additive gene action predominates in controlling grain iron, improvement of this trait can be done through hybridization followed by simple selection through pedigree method of breeding.

4.1.4 Character Association

Among the phenotypic and genotypic correlations, correlations at phenotypic level are important. Hence correlations were calculated at phenotypic level among seven characters studied to know the nature of association existing among them. Since, two dependent characters (grain iron and grain zinc) were present in this experiment, correlations and path analyses were done separately for these two dependent characters by including only one dependent character in each experiment. But to know the relationship between these two dependent characters (grain iron and grain zinc), correlation was done using all the seven characters studied irrespective of dependent character. These results are presented in Table 4.17 and are discussed hereunder.

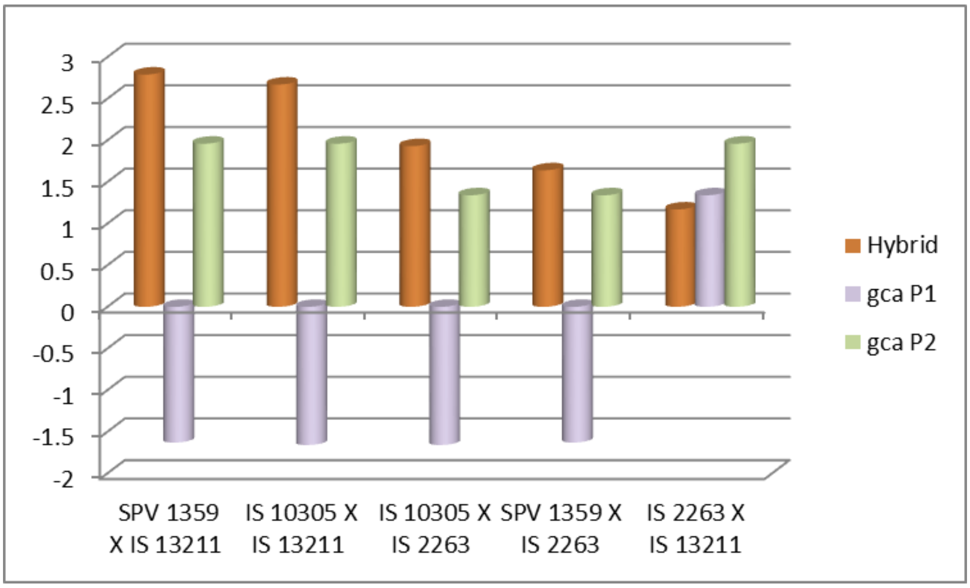

Figure 4.4. *sca* effects of promising hybrids along with the *gca* effects of both their parents for grain iron across the seasons

P1 = Parent 1 **P2 = Parent 2**

Table 4.17. Phenotypic and genotypic correlation co-efficient matrix of grain iron content with various agronomic traits during *postrainy* seasons, 2010 and 2011

Character	Plant height (m)	Days to 50 % flowering	Plant aspect score	100-grain weight (g)	Grain yield (t ha^{-1})	Correlation with grain iron
Plant height (m)	1.000	-0.318* (-0.459**)	-0.337* (-0.555*)	0.870** (1.000**)	0.714** (0.877**)	0.064 (-0.013)
Days to 50 % flowering	0.377** (0.468**)	1.000	0.331* (0.436**)	-0.307* (-0.405**)	-0.330* (-0.356*)	-0.049 (-0.093)
Plant aspect score	-0.696** (-0.788**)	-0.191 (-0.320*)	1.000	-0.382** (-0.484**)	-0.425** (-0.637**)	0.237 (0.404**)
100-grain weight (g)	0.877** (0.953**)	0.370** (0.447**)	-0.757** (-0.882**)	1.000	0.764** (0.880**)	-0.047 (-0.010)
Grain yield (t ha^{-1})	0.811** (0.873**)	0.472** (0.581**)	-0.767** (-0.891**)	0.901** (0.922**)	1.000	-0.228 (-0.220)
Grain iron (mg kg^{-1})	-0.133 (-0.154)	0.224 (0.275)	0.372** (0.580**)	-0.097 (-0.163)	-0.177 (-0.234)	1.000

'*' indicates significance at 5 % probability *i.e.*, r=>0.2845

'**' indicates significance at 1 % probability *i.e.*, r=>0.3683

Values in parenthesis indicates genotypic correlation co-efficients

Values above diagonal represent the correlations among various characters in *post-rainy* season, 2010 and below diagonal represent the correlations among various characters in *post-rainy* season, 2011

4.1.4.1 Grain Iron with all the Agronomic Characters: The correlation between plant height and grain iron was positive (r = 0.064) in 2010, whereas negative (r = -0.133) in 2011. Similarly, negative association was observed between days to 50 % flowering and grain iron (r = -0.049) in 2010, while positive association (r = 0.223) was found in 2011. This type of contradictory results in two seasons indicated high influence of environment on phenotypic expression of these characters. The non-significant association of plant height and days to 50 % flowering with grain iron indicated that sorghum grain iron and zinc contents could be improved in different maturity and plant stature backgrounds. Grain iron showed negative association with 100-grain weight and grain yield consistently in both the seasons. Their non-significant and lower magnitude of negative correlation with grain iron suggested that it is possible to enhance grain iron and zinc contents in high yielding backgrounds with large grain, which was in agreement with the report of Reddy *et al.* (2005).

4.1.4.2 Correlation among all the Agronomic Characters: Highly significant positive correlation was observed between plant height and 100-grain weight (r = 0.870) followed by 100-grain weight and grain yield (r = 0.764) and plant height and grain yield (r = 0.714) in 2010. Days to 50 % flowering showed negative correlation with both grain weight and grain yield in 2010 which would be desirable. However, there were no negative correlations among the agronomic characters in 2011. Highest significant positive correlations were recorded by 100-grain weight with grain yield (r = 0.901) followed by plant height with 100-grain weight (r = 0.877), plant height with grain yield (r = 0.811), days to 50 % flowering with grain yield (r = 0.472) and days to 50 % flowering with 100-grain weight (r = 0.370). Days to 50 % flowering showed contrary results between the two seasons in association with other characters. Liang *et al*. (1969), Patel *et al*. (1980) and Haris (2001) observed significant positive correlation between days to flowering and grain yield. There was found to be consistent positive significant association for plant height with 100-grain weight and grain yield and for 100-grain weight with grain yield in both the seasons indicating the possibility to develop high yielding varieties with tall stature and bold grains. These results were in agreement with the reports of Nimbalkar *et al*. (1988), Asthana *et al*. (1997), Jeyaprakash *et al.* (1997), Haris (2001), Patil *et al.* (1995) and Veerabadhiran *et al.* (1994).

4.1.5 Path Analysis

The correlation co-efficient measures the relationship existing between pair of characters. A dependent character is an interaction product of many mutually associated component characters and change in any one component will disturb whole network of cause and effect system. The path co-efficient analysis, a statistical device developed by Wright (1921), which takes into account the cause and effect relation between the variable, is unique in partitioning the association into direct and indirect effects through other independent variables. The path co-efficient analysis also measures the relative importance of causal factors involved. This is simply a standardized partial regression analysis, wherein total correlation value is subdivided into causal scheme. In the present study, the path co-efficient analysis was carried out for two dependent characters separately in each season at phenotypic level and the results are discussed below. By partitioning the phenotypic correlation, the direct effect of a chosen trait on grain iron and zinc and its indirect effect through other characters were computed and are presented in Tables 4.18 and 4.19.

4.1.5.1 During *postrainy* season, 2010: Among all the characters, only plant height had positive direct effect (0.506) on grain iron and also it had positive indirect effect through days to 50 % flowering (0.046) on grain iron. Hence, plant height can be used for direct selection to enhance the grain iron content. However, it had negative effect through grain yield (-0.344) followed by 100-grain weight (-0.069). Highest negative direct effect was showed by grain yield (-0.482) followed by days to 50 % flowering (-0.144) and 100-grain weight (-0.079), suggesting that there was improper relationship between yield and grain iron and it is difficult to improve the micronutrients in high yielding background. However, grain yield had positive effect through plant height (0.361) followed by days to 50 % flowering (0.047), while negative effect through 100-grain weight (-0.061) on grain iron. Days to 50 % flowering had negative effect through plant height (-0.161), while positive effect through grain yield (0.159) followed by 100-grain weight (0.024). 100-grain weight had positive effect on grain iron through plant height (0.440) followed by days to 50 % flowering (0.044) suggesting the role of grain weight in increasing the grain iron content. However, it had negative effect through grain yield.

4.1.5.2 During *postrainy* season, 2011: 100-grain weight (0.743) followed by days to 50 % flowering (0.331) had highest positive direct effect, while grain yield (-0.464) followed by plant height (-0.167) had highest negative direct effect on grain iron. Hence, grain weight can be used in direct selection for increasing the grain iron. Both plant height and days to 50 % flowering were positively influenced through 100-grain weight and negatively influenced the grain iron through grain yield. Plant height was positively influenced through days to 50 % flowering (0.125), while days to 50 %

Table 4.18. Phenotypic path matrix showing direct and indirect effects of various agronomic traits on grain iron during *postrainy* season, 2010

Character	Plant height (m)	Days to 50 % flowering	Plant aspect score	100-grain weight (g)	Grain yield (t ha^{-1})	Correlation with grain iron
Plant height (m)	**0.506**	0.046	-0.074	-0.069	-0.344	0.064
Days to 50 % flowering	-0.161	**-0.144**	0.073	0.024	0.159	-0.049
Plant aspect ratio	-0.170	-0.048	**0.220**	0.030	0.205	0.237
100-grain weight (g)	0.440	0.044	-0.084	**-0.079**	-0.368	-0.047
Grain yield (t ha^{-1})	0.361	0.047	-0.093	-0.061	**-0.482**	-0.228

Residual effect = 0.836

Bold values in diagonal represents direct effects

Table 4.19. Phenotypic path matrix showing direct and indirect effects of various agronomic traits on grain iron during *postrainy* season, 2011

Character	Plant height (m)	Days to 50 % flowering	Plant aspect score	100-grain weight (g)	Grain yield (t ha^{-1})	Correlation with grain iron
Plant height (m)	**-0.167**	0.125	-0.366	0.651	-0.376	-0.133
Days to 50 % flowering	-0.063	**0.331**	-0.101	0.275	-0.219	0.224
Plant aspect score	0.116	-0.063	**0.526**	-0.562	0.356	0.372
100-grain weight (g)	-0.146	0.123	-0.398	**0.743**	-0.418	-0.097
Gain yield (t ha^{-1})	-0.135	0.157	-0.403	0.670	**-0.464**	-0.177

Residual effect = 0.836

Bold values in diagonal represents direct effects

flowering was negatively influenced through plant height (-0.063). Both 100-grain weight and grain yield were positively influenced through days to 50 % flowering, while negatively influenced through plant height. 100-grain weight was negatively influenced through grain yield (-0.418), while grain yield was positively influenced through 100-grain weight (0.670). All characters which had positive direct effect on grain iron showed positive correlation and vice-versa. However, due to the higher overall negative indirect effects through other characters than its positive direct effect, 100-grain weight showed negative correlation with grain iron (r = -0.096). In such a situation, direct selection for this trait should be practiced to reduce the undesirable indirect effect. Indirect effects of all characters through plant height and grain yield were negative, while through days to 50 % flowering and 100-grain weight were positive.

Grain yield showed negative direct effect on grain iron in both seasons. Plant height was positively effected through days to 50 % flowering, while negatively effected through grain yield. However, days to 50 % flowering was negatively effected through plant height. 100-grain weight was negatively influenced through grain yield in both the seasons. All these results indicated that there is meagre possibility to increase the grain iron content by increasing the grain yield.

4.2 HETEROSIS AND COMBINING ABILITY STUDIES FOR GRAIN ZINC IN SORGHUM USING CONTRASTING PARENTS FOR GRAIN ZINC

The data collected on six characters, *viz.*, plant height, days to 50 % flowering, plant aspect score, 100-grain weight, grain yield and grain zinc content in the present study on evaluation of four parents and twelve crosses developed by crossing the parents in a full-diallel fashion along with one standard check (ICSR 40) were subjected to suitable statistical analyses and the results are presented below under the following heads.

1. Analysis of variance
2. Heterosis
3. Combining ability analysis
4. Character association
5. Path coefficient analysis

4.2.1 Analysis of Variance for Different Characters

The analysis of variance (Table 4.20 and 4.21) revealed the presence of significant genetic differences among the genotypes for all the characters studied in this

Table 4.20. Analysis of variance for various agronomic characters and grain zinc content in sorghum during *postrainy* season, 2010

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain zinc (mg Kg^{-1})
Replications	2	0.07	5.55**	0.09	1.71	30.15
Genotypes	16	0.48**	69.84**	0.82**	10.39**	349.82**
Error	32	0.02	0.49	0.17	0.71	30.02

Table 4.21. Analysis of variance for various agronomic characters and grain zinc content in sorghum during *postrainy* season, 2011

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain zinc (mg Kg^{-1})
Replications	2	0.00	3.55	0.44	0.43	7.91
Genotypes	16	0.52**	1.37	0.49*	9.96**	444.42**
Error	32	0.03	3.30	0.22	0.27	27.23

* indicates significance @ 5 % level of probability;
** indicates significance @ 1 % level of probability

investigation in both the *postrainy* seasons, 2010 and 2011. However, days to 50 % flowering had non-significant variation among the genotypes during *postrainy* season, 2011.The pooled analysis of variance (Table 4.22) across the two *postrainy* seasons showed that the genotypes exhibited significant variation for all the traits under study. The genotype x environment interaction was highly significant for all the characters. However, environment was found to have non-significant influence on 100-grain weight and grain zinc content.

4.2.1.1 Mean Performance of Parents and Crosses: The mean performance of parents, hybrids and standard check for seven characters (Tables 4.23, 4.24 and 4.25) are discussed hereunder characterwise:

4.2.1.1.1 Plant Height (m): The mean values for plant height varied from 1.10 m (ICSB 56) to 2.40 m (IS 20843) with a grand mean of 2.05 m in 2010, from 1.13 m (ICSB 56) to 2.50 m (IS 20843 X IS 2248) with a grand mean of 1.96 m in 2011 and from 1.12 m (ICSB 56) to 2.42 m (IS 20843 X IS 2248) with a general mean of 2.00 m across the seasons. IS 20843 recorded significantly higher plant height and it was significantly taller than all other parents in both the seasons and across the seasons except IS 2248 in 2010. All the crosses recorded significantly higher plant height than the check in both the seasons and across the seasons. Among the crosses, IS 2248 X IS 20843, IS 2248 X PVK 801 and PVK 801 X IS 20843 (2.37 m) recorded highest plant height in 2010 and recorded significantly higher plant height than all other crosses except IS 20843 X PVK 801, IS 2248 X PVK 801, PVK 801 X IS 2248 and IS 2248 X PVK 801 in 2010 recorded highest plant height, while IS 20843 X IS 2248 was significantly taller than IS 2248 X ICSB 56, PVK 801 X ICSB 56, ICSB 56 X IS 2248, ICSB 56 X IS 20843 and ICSB 56 X PVK 801 in 2011 and across the seasons.

4.2.1.1.2 Days to 50 % Flowering: Days to 50 % flowering varied from 73 days (PVK 801 X IS 2248) to 93.67 days (IS 20843) with a grand mean of 78.27 days in 2010, from 67.33 days (IS 20843) to 70.33 days (PVK 801 and ICSB 56 X PVK 801) with a grand mean of 69.45 days and from 71.34 days (PVK 801 X IS 2248) to 80.50 days (IS 20843) with a general mean of 73.86 days. Among the parents, IS 2248 was the earliest and it was significantly earlier than other parents in 2010 and across the seasons. IS 20843 was the earliest to flower and it was significantly earlier than PVK 801 in 2011. Among the hybrids, PVK 801 X IS 2248 was the earliest and significantly earlier than all other crosses in 2010 and across the seasons. PVK 801 X ICSB 56, IS 20843 X IS 2248 and PVK 801 X IS 20843 were earliest among crosses but, none of these

Table 4.22. Pooled analysis of variance for various agronomic characters and grain zinc content in sorghum

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain zinc (mg Kg^{-1})
Replication	4	0.03	6.24**	0.26	1.99	19.03
Genotypes (G)	16	0.92**	67.91**	0.74**	34.68**	461.00**
Environments (E)	1	0.22**	139572.78**	0.13	71.62**	107.06
G X E interaction	16	0.08**	76.06**	0.56**	16.62**	333.24**
Error	64	0.02	1.00	0.19	1.00	28.62

* indicates significance @ 5 % level of probability;

** indicates significance @ 1 % level of probability

Table 4.23. Mean performance of parents contrasting for grain zinc and their hybrids for plant height (m) and days to 50 % flowering in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Plant height (m)			Days to 50 % flowering		
	2010	2011	POOLED	2010	2011	POOLED
PARENTS						
IS 2248	2.17	1.57	1.87	78.00	69.67	73.84
IS 20843	2.40	2.05	2.23	93.67	67.33	80.50
PVK 801	1.53	1.47	1.50	80.67	70.33	75.50
ICSB 56	1.10	1.13	1.12	80.33	69.67	75.00
MEAN	1.80	1.56	1.68	83.17	69.25	76.21
DIRECT CROSSES						
IS 2248 X IS 20843	2.37	2.33	2.35	77.67	69.67	73.67
IS 2248 X PVK 801	2.37	2.17	2.27	80.00	69.67	74.84
IS 2248 X ICSB 56	2.17	2.08	2.13	79.67	69.67	74.67
IS 20843 X PVK 801	2.33	2.3	2.32	76.33	69.67	73.00
IS 20843 X ICSB 56	1.90	2.27	2.09	77.00	69.67	73.34
PVK 801 X ICSB 56	2.10	1.8	1.95	77.67	69.00	73.34
MEAN	2.21	2.16	2.18	78.06	69.56	73.81
RECIPROCAL CROSSES						
IS 20843 X IS 2248	2.33	2.50	2.42	77.67	69.00	73.34
PVK 801 X IS 2248	2.30	2.17	2.24	73.00	69.67	71.34
PVK 801 X IS 20843	2.37	2.40	2.39	78.33	69.00	73.67
ICSB 56 X IS 2248	2.10	2.03	2.07	76.67	69.67	73.17
ICSB 56 X IS 20843	2.07	2.17	2.12	76.33	69.67	73.00
ICSB 56 X PVK 801	2.00	1.60	1.80	78.33	70.33	74.33
MEAN	2.20	2.15	2.17	76.72	69.56	73.14
ICSR 40 (CHECK)	1.22	1.22	1.22	69.33	69.00	69.17
GRAND MEAN	2.05	1.96	2.01	78.27	69.45	73.86
C.V.%	7.15	8.33	7.74	0.89	2.62	1.76
C.D. (5%)	0.24	0.27	0.26	1.16	3.02	2.09
S Em	0.08	0.09	0.09	0.40	1.05	0.73

Table 4.24. Mean performance of parents contrasting for grain zinc and their hybrids for plant aspect score and 100 grain weight (g) in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Plant aspect score			100 grain weight (g)		
	2010	2011	POOLED	2010	2011	POOLED
PARENTS						
IS 2248	3.00	2.67	2.84	3.19	2.97	3.08
IS 20843	3.33	2.67	3.00	2.14	3.20	2.67
PVK 801	2.33	1.67	2.00	3.59	3.15	3.37
ICSB 56	2.33	2.67	2.50	2.69	2.75	2.72
MEAN	2.75	2.42	2.58	2.90	3.02	2.96
DIRECT CROSSES						
IS 2248 X IS 20843	3.00	3.00	3.00	3.48	3.61	3.55
IS 2248 X PVK 801	3.00	2.67	2.84	3.41	3.77	3.59
IS 2248 X ICSB 56	2.67	3.67	3.17	4.10	3.20	3.65
IS 20843 X PVK 801	3.33	2.00	2.67	3.80	3.58	3.69
IS 20843 X ICSB 56	3.00	1.67	2.34	2.68	3.11	2.90
PVK 801 X ICSB 56	2.33	1.33	1.83	3.47	2.60	3.04
MEAN	2.89	2.39	2.64	3.49	3.31	3.40
RECIPROCAL CROSSES						
IS 20843 X IS 2248	3.00	2.00	2.50	3.56	3.61	3.59
PVK 801 X IS 2248	2.33	1.67	2.00	3.95	3.55	3.75
PVK 801 X IS 20843	3.00	1.33	2.17	3.09	3.77	3.43
ICSB 56 X IS 2248	2.33	1.67	2.00	3.64	2.36	3.00
ICSB 56 X IS 20843	3.00	2.33	2.67	2.64	3.19	2.92
ICSB 56 X PVK 801	2.00	1.33	1.67	3.47	3.08	3.28
MEAN	2.61	1.72	2.17	3.39	3.26	3.33
ICSR 40 (CHECK)	2.00	3.33	2.67	3.03	3.20	3.12
GRAND MEAN	2.70	2.22	2.46	3.29	3.22	3.25
C.V.%	19.83	19.92	19.88	12.61	14.49	13.55
C.D. (5%)	0.89	0.73	0.81	0.69	0.78	0.74
S Em	0.31	0.25	0.28	0.24	0.27	0.26

Table 4.25. Mean performance of parents contrasting for grain zinc and their hybrids for grain yield (t ha^{-1}) and grain zinc (mg kg^{-1}) in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Grain yield (t ha^{-1})			Grain zinc (mg kg^{-1})		
	2010	**2011**	**POOLED**	**2010**	**2011**	**POOLED**
PARENTS						
IS 2248	4.50	2.42	3.46	58.67	32.73	45.70
IS 20843	3.28	4.75	4.02	47.73	32.57	40.15
PVK 801	6.67	5.41	6.04	49.13	23.07	36.10
ICSB 56	2.69	2.78	2.74	34.03	25.40	29.72
MEAN	4.29	3.84	4.06	47.39	28.44	37.92
DIRECT CROSSES						
IS 2248 X IS 20843	5.93	3.57	4.75	51.87	58.20	55.04
IS 2248 X PVK 801	4.61	2.93	3.77	37.60	53.47	45.54
IS 2248 X ICSB 56	8.62	1.48	5.05	22.17	53.80	37.99
IS 20843 X PVK 801	7.69	7.52	7.61	34.13	29.27	31.70
IS 20843 X ICSB 56	7.91	6.92	7.42	33.47	28.67	31.07
PVK 801 X ICSB 56	7.07	6.16	6.62	30.13	23.00	26.57
MEAN	6.97	4.76	5.87	34.90	41.07	37.98
RECIPROCAL CROSSES						
IS 20843 X IS 2248	5.48	3.17	4.33	54.43	45.77	50.10
PVK 801 X IS 2248	6.10	4.55	5.33	31.63	52.83	42.23
PVK 801 X IS 20843	6.05	7.33	6.69	31.40	28.50	29.95
ICSB 56 X IS 2248	6.05	3.61	4.83	40.57	40.03	40.30
ICSB 56 X IS 20843	6.95	6.28	6.62	35.37	28.67	32.02
ICSB 56 X PVK 801	8.80	5.00	6.90	23.00	23.87	23.44
MEAN	6.57	4.99	5.78	36.07	36.61	36.34
ICSR 40 (CHECK)	3.01	3.59	3.30	29.57	30.23	29.90
GRAND MEAN	5.97	4.56	5.26	37.94	35.89	36.91
C.V.%	14.14	11.43	12.79	14.44	14.54	14.49
C.D. (5%)	1.40	0.87	1.14	9.11	8.68	8.90
S E m	0.49	0.30	0.40	3.16	3.01	3.09

crosses were significantly earlier than all other crosses in 2011. Across the seasons, cross PVK 801 X IS 2248 was earliest to flower and it was significantly earlier than IS 2248 X PVK 801, IS 2248 X ICSB 56, ICSB 56 X PVK 801, IS 2248 X IS 20843 and PVK 801 X IS 20843. Compared to check, all the genotypes flowered late in both the seasons and across the seasons.

4.2.1.1.3 Plant Aspect Score: The scoring ranged from 2.00 (ICSB 56 X PVK 801) to 3.33 (IS 20843 and IS 20843 X PVK 801) with a grand mean of 2.71 in 2010, from 1.33 (PVK 801 X ICSB 56, PVK 801 X IS 20843 and ICSB 56 X PVK 801) to 3.67 (IS 2248 X ICSB 56) with a grand mean of 2.22 in 2011 and from 1.67 (ICSB 56 X PVK 801) to 3.17 (IS 2248 X ICSB 56) with a general mean of 2.46 across the seasons. PVK 801 and ICSB 56 were agronomically desirable among all the parents and significantly desirable than IS 20843 in 2010, while PVK 801 in 2011 and across the seasons was most agronomically desirable among the parents and significantly desirable than all other parents. Among the crosses, ICSB 56 X PVK 801 was the most desirable in 2010 and across the seasons. This was significantly desirable than all crosses except IS 2248 X PVK 801, PVK 801 X ICSB 56, PVK 801 X IS 2248 and ICSB 56 X IS 2248 in 2010 while, significantly desirable than all other crosses except PVK 801 X ICSB 56, PVK 801 X IS 2248, ICSB 56 X IS 2248, PVK 801 X IS 20843 and IS 20843 X ICSB 56 across the seasons. Compared to check, none of the crosses were agronomically desirable in 2010, while all crosses were agronomically desirable in 2011.

4.2.1.1.4 100-grain weight (g): 100-grain weight varied from 2.14 g (IS 20843) to 4.10 g (IS 2248 X ICSB 56) with a grand mean of 3.29 g in 2010, from 2.36 g (ICSB 56 X IS 2248) to 3.77 g (IS 2248 X PVK 801 and PVK 801 X IS 20843) with a grand mean of 3.22 g in 2011 and from 2.67 (IS 20843) to 3.75 g (PVK 801 X IS 2248) with a general mean of 3.25 g across the seasons. PVK 801 recorded the highest grain weight in 2010 and across the seasons and IS 20843 in 2011 recorded the highest grain weight among the parents. PVK 801 recorded significantly higher grain weight than IS 20843 and ICSB 56 in both the seasons and across the seasons. IS 2248 X ICSB 56 in 2010, IS 2248 X PVK 801 and PVK 801 X IS 20843 in 2011 and PVK 801 X IS 2248 across the seasons recorded the highest grain weight among the crosses. Compared to check, none of the genotypes recorded higher grain weight in both the seasons and across the seasons, barring crosses, IS 2248 X ICSB 56, IS 20843 X PVK 801 and PVK 801 X IS 2248 in 2010. IS 2248 X ICSB 56 recorded significantly higher grain weight than PVK 801 X IS 20843, IS 20843 X ICSB 56 and ICSB 56 X IS 20843 in 2010 while, PVK 801 X IS 20843 recorded significantly higher grain weight than PVK 801 X ICSB 56 and ICSB 56 X IS 2248 in 2011. Across the seasons, PVK 801 X IS 2248 recorded significantly higher grain weight than IS 20843 X ICSB 56 and its reciprocal cross.

4.2.1.1.5 Grain Yield (t ha^{-1}): The mean values of grain yield ranged from 2.69 t ha^{-1} (ICSB 56) to 8.80 t ha^{-1} (ICSB 56 X PVK 801) with a grand mean of 5.97 t ha^{-1} in 2010, from 1.48 t ha^{-1} (IS 2248 X ICSB 56) to 7.52 t ha^{-1} (IS 20843 X PVK 801) with a grand mean of 4.56 t ha^{-1} in 2011 and from 2.74 t ha^{-1} (ICSB 56) to 7.61 (IS 20843 X PVK 801) with a general mean of 5.26 t ha^{-1} across the seasons. The highest grain yield was recorded by PVK 801 in both the seasons and across the seasons, among the parents and also recorded significantly higher grain yield than the check and other parents in both the seasons and across the seasons. ICSB 56 X PVK 801 in 2010 and IS 20843 X PVK 801 in 2011 and across the seasons recorded the highest grain yield among the crosses. All crosses recorded higher grain yield than check in 2010. More than 50 % of the crosses recorded significantly higher grain yield than the check across the seasons. IS 20843 X PVK 801 exhibited significantly higher grain yield than all crosses except IS 20843 X ICSB 56, ICSB 56 X PVK 801 and PVK 801 X IS 20843 in 2011 and except IS 20843 X ICSB 56, ICSB 56 X IS 20843 and PVK 801 X ICSB 56 across the seasons.

4.2.1.1.6 Grain Zinc (mg kg^{-1}): Grain zinc ranged from 22.17 mg kg^{-1} (IS 2248 X ICSB 56) to 58.67 mg kg^{-1} (IS 2248) in 2010 with a grand mean of 37.94 mg kg^{-1}, from 23.00 mg kg^{-1} (PVK 801 X ICSB 56) to 58.20 mg kg^{-1} (IS 2248 X IS 20843) with a grand mean of 35.89 mg kg^{-1}in 2011 and from 23.44 mg kg^{-1} (ICSB 56 X PVK 801) to 55.04 mg kg^{-1} (IS 2248 X IS 20843) with a grand mean of 36.91 mg kg^{-1} across the seasons. Among the parents, IS 2248 recorded the highest grain zinc consistently in both the seasons and across the seasons. All the parents except ICSB 56 recorded significantly higher grain zinc than the check in 2010, while none of the parents recorded significantly higher grain zinc than the check in 2011. Among the crosses, IS 20843 X IS 2248 recorded the highest grain zinc and recorded significantly higher grain zinc than all other crosses except its reciprocal cross in 2010 and across the seasons. IS 2248 X IS 20843 recorded significantly higher grain zinc than all other crosses except IS 2248 X ICSB 56, IS 2248 X PVK 801 and PVK 801 X IS 2248 in 2011. Across the seasons also, the same cross, IS 2248 X IS 20843 exhibited significantly superior performance over all the other crosses except IS 20843 X IS 2248 (Fig 4.5).

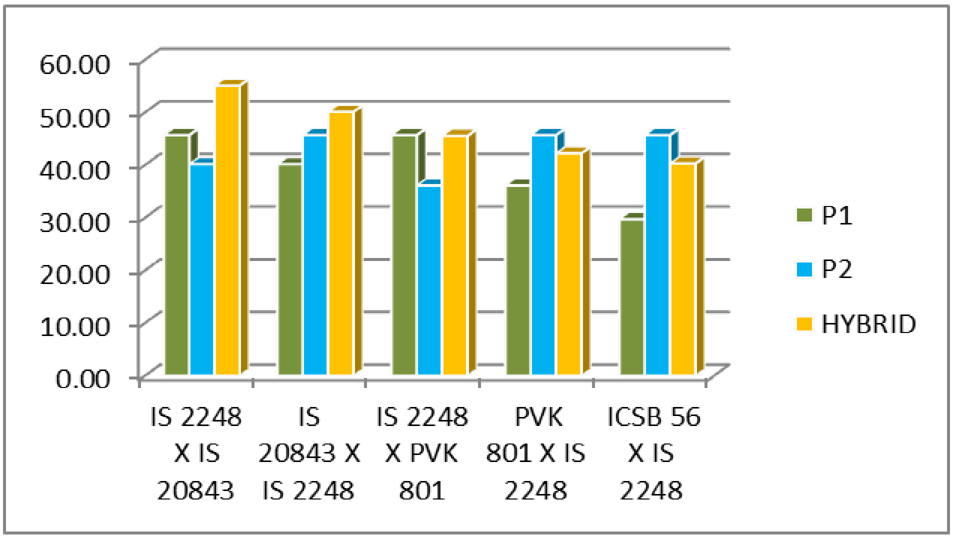

Figure 4.5. ***Per se*** **performance of promising hybrids along with parents for grain zinc across the seasons**

P1 = Parent 1 **P2 = Parent 2**

4.2.2 Heterosis

Heterosis of different quantitative traits among direct crosses and reciprocal crosses are presented in Tables 4.26 to 4.30 and are discussed hereunder:

4.2.2.1 Plant Height (m): Heterosis over mid-parent ranged from 2.19 % (IS 20843 X IS 2248) to 59.49 % (PVK 801 X ICSB 56) in 2010, from 23.08 % (ICSB 56 X PVK 801) to 54.32 % (IS 2248 X ICSB 56) in 2011 and from 14.95 % (IS 2248 X IS 20843) to 49.04 % (PVK 801 X ICSB 56) across the seasons. Almost all crosses recorded significant positive heterosis over mid-parent in both the seasons, barring three crosses (IS 20843 X ICSB 56, IS 2248 X IS 20843 and IS 20843 X IS 2248) which exhibited non-significant positive heterosis in 2010. PVK 801 X ICSB 56 in 2010 and across the seasons and IS 2248 X ICSB 56 in 2011 showed highest positive heterosis, while lowest heterosis was recorded by IS 20843 X IS 2248, ICSB 56 X PVK 801 and IS 2248 X IS 20843 in 2010, 2011 and across the seasons, respectively.

Heterosis over better parent varied from -20.83 % (IS 20843 X ICSB 56) to 36.96 % (PVK 801 X ICSB 56) in 2010, from 5.69 % (ICSB 56 X IS 20843) to 38.30 % (IS 2248 X PVK 801 and PVK 801 X IS 2248) in 2011 and from -6.37 % (IS 20843 X ICSB 56) to 30.00 % (PVK 801 X ICSB 56) across the seasons. Highest positive significant heterosis was recorded by PVK 801 X ICSB 56 in 2010 and across the seasons and IS 2248 X PVK 801 and PVK 801 X IS 2248 in 2011. Two crosses (PVK 801 X ICSB 56 and ICSB 56 X PVK 801) recorded significant positive heterosis over better parent in 2010. IS 2248 X PVK 801, IS 2248 X ICSB 56, and PVK 801 X IS 2248 exhibited significant positive heterosis in 2011 and across the seasons. In addition to these crosses, IS 20843 X IS 2248, PVK 801 X IS 20843 and ICSB 56 X IS 2248 in 2011 and ICSB 56 X PVK 801 across the seasons recorded significant positive heterosis, while least heterosis was exhibited by IS 20843 X ICSB 56 in 2010 and across the seasons and ICSB 56 X IS 20843 in 2011.

Heterosis over standard check ranged from 56.16 % (IS 20843 X ICSB 56) to 94.79 % (IS 2248 X IS 20843) in 2010, from 31.51 % (ICSB 56 X PVK 801) to 105.48 % (IS 20843 X IS 2248) in 2011 and from 47.95 % (ICSB 56 X PVK 801) to 98.63 % (IS 20843 X IS 2248) across the seasons. All the crosses recorded highly significant positive heterosis over standard check in individual seasons. Maximum standard heterosis was recorded by IS 2248 X IS 20843 in 2010 and its reciprocal cross in 2011 and across the seasons, while minimum heterosis over check was exhibited by IS 20843 X ICSB 56 in 2010 and ICSB 56 X PVK 801 in 2011 and across the seasons.

Table 4.26. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for plant height in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2248 X IS 20843	2.37	3.80	-1.25	94.79**	2.33	29.03**	13.82	91.78**	2.35	14.95**	5.69	93.29**
IS 2248 X PVK 801	2.37	27.93**	9.23	94.52**	2.17	42.86**	38.30**	78.08**	2.27	34.65**	21.43**	86.30**
IS 2248 X ICSB 56	2.17	32.65**	0.00	78.08**	2.08	54.32**	32.98**	71.23**	2.13	42.46**	13.84*	74.66**
IS 20843 X PVK 801	2.33	18.64**	-2.78	91.78**	2.30	30.81**	12.20	89.04**	2.32	24.38**	4.12	90.41**
IS 20843 X ICSB 56	1.90	8.57	-20.83**	56.16**	2.27	42.41**	10.57	86.30**	2.08	24.69**	-6.37	71.23**
PVK 801 X ICSB 56	2.10	59.49**	36.96**	72.60**	1.80	38.46**	22.73*	47.95**	1.95	49.04**	30.00**	60.27**

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.26 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**
RECIPROCAL CROSSES												
IS 20843 X IS 2248	2.33	2.19	-2.78	91.78**	2.50	38.25**	21.95**	105.48**	2.42	18.13**	8.61	98.63**
PVK 801 X IS 2248	2.30	24.32**	6.15	89.04**	2.17	42.86**	38.30**	78.08**	2.23	32.67**	19.64**	83.56**
PVK 801 X IS 20843	2.37	20.34**	-1.39	94.52**	2.40	36.49**	17.07*	97.26**	2.38	27.96**	7.12	95.89**
ICSB 56 X IS 2248	2.10	28.57**	-3.08	72.60**	2.03	50.62**	29.79**	67.12**	2.07	38.55**	10.71	69.86**
ICSB 56 X IS 20843	2.07	18.10**	-13.89**	69.86**	2.17	36.13**	5.69	78.08**	2.12	26.68**	-4.87	73.97**
ICSB 56 X PVK 801	2.00	51.9**	30.43**	64.38**	1.60	23.08*	9.09	31.51**	1.80	37.58**	20.00*	47.95**
C.D. (5%)		0.20	0.24	0.24		0.24	0.29	0.29		0.20	0.24	0.24
C.D. (1%)		0.27	0.33	0.33		0.33	0.38	0.38		0.27	0.33	0.33

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.27. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for days to 50 % flowering in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2248 X IS 20843	77.67	-9.51**	-0.43	12.02**	69.67	1.70	3.47	0.97	74.85	-6.88**	-0.32	8.93**
IS 2248 X PVK 801	80.00	0.84	2.56**	15.38**	69.67	-0.48	0.00	0.97	76.52	0.51	1.91	11.40**
IS 2248 X ICSB 56	79.67	0.63	2.14**	14.90**	69.67	0.00	0.00	0.97	76.29	0.47	1.59	11.05**
IS 20843 X PVK 801	76.33	-12.43**	-5.37**	10.10**	69.67	1.21	3.47	0.97	73.90	-9.25**	-4.26**	7.57**
IS 20843 X ICSB 56	77.00	-11.49**	-4.15**	11.06**	69.67	1.70	3.47	0.97	74.37	-8.43**	-3.11**	8.27**
PVK 801 X ICSB 56	77.67	-3.52**	-3.32**	12.02**	69.00	-1.43	-0.96	0.00	74.67	-3.00**	-2.73*	8.70**

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.27 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**
RECIPROCAL CROSSES												
IS 20843 X IS 2248	77.67	-9.51**	-0.43	12.02**	69.00	0.73	2.48	0.00	74.67	-7.11**	-0.56	8.70**
PVK 801 X IS 2248	73.00	-7.98**	-6.41**	5.29**	69.67	-0.48	0.00	0.97	71.51	-6.08**	-4.77**	4.09**
PVK 801 X IS 20843	78.33	-10.13**	-2.89**	12.98**	69.00	0.24	2.48	0.00	74.14	-8.96**	-3.95**	7.92**
ICSB 56 X IS 2248	76.67	-3.16**	-1.71*	10.58**	69.67	0.00	0.00	0.97	75.15	-1.03	0.07	9.39**
ICSB 56 X IS 20843	76.33	-12.26**	-4.98**	10.10**	69.67	1.70	3.47	0.97	73.90	-9.02**	-3.74**	7.57**
ICSB 56 X PVK 801	78.33	-2.69**	-2.49**	12.98**	70.33	0.48	0.96	1.93	75.51	-1.90*	-1.63	9.93**
C.D. (5%)		1.00	1.16	1.16		2.61	3.01	3.01		1.42	1.64	1.64
C.D. (1%)		1.34	1.56	1.56		3.50	4.05	4.05		1.89	2.18	2.18

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.28. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for 100-grain weight in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2248 X IS 20843	3.48	30.71**	9.20	14.96	3.61	17.00	12.80	12.92	3.55	23.35*	32.81*	13.91
IS 2248 X PVK 801	3.41	0.64	-4.93	12.54	3.77	22.96*	19.45	17.81	3.59	11.24	16.44	15.20
IS 2248 X ICSB 56	4.10	39.42**	28.42*	35.20**	3.20	11.94	7.74	0.10	3.65	25.86*	34.27*	17.17
IS 20843 X PVK 801	3.80	32.71**	5.95	25.41*	3.58	12.74	11.86	11.98	3.69	22.21*	38.18**	18.51
IS 20843 X ICSB 56	2.68	10.91	-0.37	-11.66	3.11	4.59	-2.81	-2.71	2.90	7.42	8.36	-7.06
PVK 801 X ICSB 56	3.47	10.63	-3.25	14.52	2.60	-12.03	-17.65	-18.85	3.03	-0.36	11.59	-2.62

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.28 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**
RECIPROCAL CROSSES												
IS 20843 X IS 2248	3.56	33.71**	11.70	17.60	3.61	16.89	12.70	12.81	3.59	24.68*	34.25*	15.14
PVK 801 X IS 2248	3.95	16.67	10.22	30.47*	3.55	15.89	12.58	10.94	3.75	16.30	21.74	20.44
PVK 801 X IS 20843	3.09	7.80	-13.94	1.87	3.77	18.62	17.69	17.81	3.43	13.49	28.32*	10.06
ICSB 56 X IS 2248	3.64	23.99**	14.21	20.24	2.36	-17.53	-20.63	-26.25*	3.00	3.51	10.42	-3.64
ICSB 56 X IS 20843	2.64	9.39	-1.74	-12.87	3.19	7.28	-0.31	-0.21	2.92	8.23	9.17	-6.37
ICSB 56 X PVK 801	3.47	10.52	-3.35	14.41	3.08	4.46	-2.22	-3.65	3.28	7.58	20.48	5.14
C.D. (5%)		0.59	0.69	0.69		0.67	0.77	0.77		0.62	0.72	0.72
C.D. (1%)		0.79	0.93	0.93		0.90	1.04	1.04		0.82	0.96	0.96

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.29. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for grain yield in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2248 X IS 20843	5.93	52.51**	31.78*	96.79**	3.57	-0.46	-24.89**	-0.46	6.94	20.78	39.11*	32.76*
IS 2248 X PVK 801	4.61	-17.49	-30.90**	52.88*	2.93	-25.04*	-45.75**	-18.22	5.54	-21.51*	11.14	6.07
IS 2248 X ICSB 56	8.62	139.67**	91.56**	186.06**	1.48	-43.21**	-46.88**	-58.83**	6.53	41.04**	53.03**	24.82
IS 20843 X PVK 801	7.69	54.68**	15.35	155.20**	7.52	48.03**	39.09**	109.67**	11.77	50.53**	81.04**	125.22**
IS 20843 X ICSB 56	7.91	164.99**	141.40**	162.50**	6.92	83.63**	45.51**	92.84**	11.32	110.36**	165.60**	116.64**
PVK 801 X ICSB 56	7.07	51.07**	6.05	134.62**	6.16	50.57**	14.00	71.84**	10.10	50.78**	136.97**	93.29**

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.29 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**	**MEAN**	**H1**	**H2**	**H3**
RECIPROCAL CROSSES												
IS 20843 X IS 2248	5.48	41.02*	21.85	81.97**	3.17	-11.52	-33.24**	-11.52	6.29	9.55	26.17	20.41
PVK 801 X IS 2248	6.10	9.19	-8.55	102.32**	4.55	16.18	-15.91*	26.77*	7.98	12.91	59.87**	52.57**
PVK 801 X IS 20843	6.05	21.62	-9.30	100.66**	7.33	44.36**	35.64**	104.46**	7.05	-9.88	8.38	34.83*
ICSB 56 X IS 2248	6.05	68.30**	34.52*	100.88**	3.61	38.72*	29.74	0.56	10.62	129.56**	149.08**	103.16**
ICSB 56 X IS 20843	6.95	132.83**	112.11**	130.64**	6.28	66.73**	32.12**	75.09**	10.15	88.45**	137.93**	94.07**
ICSB 56 X PVK 801	8.80	88.03**	32.00**	192.04**	5.00	22.07*	-7.58	39.31**	10.01	49.37**	134.76**	91.48**
C.D. (5%)		1.22	1.41	1.41		0.75	0.86	0.86		1.42	1.64	1.64
C.D. (1%)		1.64	1.89	1.89		1.01	1.15	1.15		1.89	2.18	2.18

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.30. Estimates of heterosis over mid-parent (H1), better parent (H2) and standard check (H3) for grain zinc in sorghum across *postrainy* seasons, 2010 and 2011

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
DIRECT CROSSES												
IS 2248 X IS 20843	51.87	-2.50	-11.59	75.42**	58.20	78.25**	77.80**	92.50**	55.04	28.23**	37.09**	84.08**
IS 2248 X PVK 801	37.60	-30.24**	-35.91**	27.17	53.47	91.64**	63.34**	76.85**	45.54	11.33	26.15*	52.31**
IS 2248 X ICSB 56	22.17	-52.18**	-62.22**	-25.03	53.80	85.09**	64.36**	77.95**	37.99	0.75	27.84	27.06
IS 20843 X PVK 801	34.13	-29.52**	-30.53**	15.45	29.27	5.21	-10.13	-3.20	31.70	-16.85	-12.19	6.02
IS 20843 X ICSB 56	33.47	-18.14	-29.88**	13.19	28.67	-1.09	-11.98	-5.18	31.07	-11.07	4.54	3.90
PVK 801 X ICSB 56	30.13	-27.54**	-38.67**	1.92	23.00	-5.09	-9.45	-23.93	26.57	-19.27	-10.60	-11.15

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

Table 4.30 (Contd.)

CROSS	2010				2011				POOLED			
	MEAN	H1	H2	H3	MEAN	H1	H2	H3	MEAN	H1	H2	H3
RECIPROCAL CROSSES												
IS 20843 X IS 2248	54.43	2.32	-7.22	84.10**	45.77	40.17**	39.82**	51.38**	50.10	16.72	24.79*	67.56**
PVK 801 X IS 2248	31.63	-41.31**	-46.08**	6.99	52.83	89.37**	61.41**	74.75**	42.23	3.26	16.99	41.25**
PVK 801 X IS 20843	31.40	-35.17**	-36.09**	6.20	28.50	2.46	-12.49	-5.73	29.95	-21.44*	-17.04	0.17
ICSB 56 X IS 2248	40.57	-12.48	-30.85**	37.20*	40.03	37.72**	22.29	32.40*	40.30	6.87	35.61*	34.78*
ICSB 56 X IS 20843	35.37	-13.49	-25.90**	19.62	28.67	-1.09	-11.98	-5.18	32.02	-8.35	7.74	7.08
ICSB 56 X PVK 801	23.00	-44.69**	-53.19**	-22.21	23.87	-1.51	-6.04	-21.06	23.44	-28.77*	-21.12	-21.61
C.D. (5%)		7.88	9.11	9.11		7.52	8.68	8.68		7.55	8.73	8.73
C.D. (1%)		10.60	12.24	12.24		10.10	11.66	11.66		10.04	11.60	11.60

* indicates significance @ 5 % level of probability and ** indicates significance @ 1 % level of probability

ICSB 56 X PVK 801 recorded lowest heterosis over mid-parent, better parent and standard check in 2011.

Almost all the crosses recorded highly significant positive heterosis in both the seasons for plant height. Similar results were reported by Bhagmal and Mishra (1985), Berenji (1988), Chinna and Phul (1988), Choudhari (1992), Biradar (1995) and Salunke and Deore (1998). Heterosis over better parent in positive direction was observed by Senthil and Palaniswamy (1993), Ganesh *et al.* (1996), Lokapur (1997) and Pawar (2000), while, Patel *et al.* (1987), Desai (1991) and Belavatagi (1997) noticed significant heterosis over commercial check. Shivanna (1989) reported positive as well as negative heterosis in different crosses. Contrarily, Patel *et al.* (1990) observed negative heterosis for this character. Significant heterosis over mid parent was obtained by Kanaka (1979), while Giriraj and Goud (1981) observed non-significant heterosis over mid parental values. PVK 801 X ICSB 56, IS 2248 X ICSB 56 and IS 20843 X IS 2248 recorded highest significant positive heterosis over mid-parent, better parent and standard check, respectively across the seasons. IS 2248 X IS 20843 recorded lowest heterosis over both their mid-parent and better parent. This cross occupied second position with regard to standard heterosis next to IS 20843 X IS 2248 suggesting that there was no significant maternal effect in the genetic control of plant height. Hence, these two crosses would be suitable for further improving the plant height for fodder purpose.

4.2.2.2 Days to 50 % Flowering: Days to 50 % flowering indicates relative duration of the genotypes. Early flowering genotypes are usually physiologically more efficient than late flowering ones and therefore it is a preferred trait. Heterosis over mid-parent for days to 50 % flowering ranged from -12.43 % (IS 20843 X PVK 801) to 0.84 % (IS 2248 X PVK 801) in 2010, from -1.43 % (PVK 801 X ICSB 56) to 1.70 % (IS 2248 X IS 20843, IS 20843 X ICSB 56 and ICSB 56 X IS 20843) in 2011 and from -9.25 % (IS 20843 X PVK 801) to 0.51 % (IS 2248 X PVK 801) across the seasons. All the crosses recorded significant negative desirable heterosis except IS 2248 X PVK 801 and IS 2248 X ICSB 56 in 2010. Almost all the crosses, barring two crosses *i.e.*, IS 2248 X PVK 801 and IS 2248 X ICSB 56 exhibited negative heterosis across the seasons, while none of the crosses exhibited significant heterosis over mid-parent in 2011. Highest negative heterosis was exhibited by IS 20843 X PVK 801 in 2010 and across the seasons and PVK 801 X ICSB 56 in 2011. None of the crosses recorded significant positive mid-parent heterosis in both the seasons. Highest positive heterosis was recorded by IS 2248 X PVK 801 in 2010, IS 2248 X IS 20843, IS 20843 X ICSB 56 and ICSB 56 X IS 20843 in 2011 and IS 2248 X PVK 801 across the seasons.

Heterosis over better parent showed variation from -6.41 % (PVK 801 X IS 2248) to 2.56 % (IS 2248 X PVK 801) in 2010, from -0.96 % (PVK 801 X ICSB 56) to 3.47 % (ICSB 56 X IS 20843, IS 2248 X IS 20843, IS 20843 X PVK 801 and IS 20843 X ICSB 56) in 2011 and from -4.77 % (PVK 801X IS 2248) to 1.91 % (IS 2248 X PVK 801) across the seasons. Out of ten significant crosses, eight were negatively heterotic in 2010, while six crosses (IS 20843 X PVK 801, IS 20843 X ICSB 56, PVK 801 X ICSB 56, PVK 801 X IS 2248, PVK 801 X IS 20843 and ICSB 56 X IS 20843 recorded significant negative heterosis over better parent across the seasons. However, none of the crosses recorded significant heterosis in 2011. IS 2248 X PVK 801 in 2010 and across the seasons and IS 2248 X IS 20843, IS 20843 X PVK 801, IS 20843 X ICSB 56 and ICSB 56 X IS 20843 in 2011 recorded highest heterosis over better parent, while highest negative heterosis was observed in PVK 801 X IS 2248 in 2010 and across the seasons and PVK 801 X ICSB 56 in 2011.

Heterosis over standard check ranged from 5.29 % (PVK 801 X IS 2248) to 15.38 % (IS 2248 X PVK 801) in 2010, from 0.00 % (PVK 801 X ICSB 56, IS 20843 X IS 2248 and PVK 801 X IS 20843) to 1.93 % (ICSB 56 X PVK 801) in 2011 and from 4.09 % (PVK 801 X IS 2248) to 11.40 % (IS 2248 X PVK 801) across the seasons. All the crosses exhibited significant positive heterosis in 2010 and across the seasons, while none of the crosses recorded significant heterosis over standard check in 2011. Highest heterosis over standard check was observed in IS 2248 X PVK 801 in 2010 and across the seasons and ICSB 56 X PVK 801 in 2011, while lowest heterosis was recorded by PVK 801 X IS 2248 in 2010 and across the seasons and PVK 801 X ICSB 56, IS 20843 X IS 2248 and PVK 801 X IS 20843 in 2011.

More than 50 per cent of the crosses recorded significant negative heterosis over mid-parent in 2010. These results were in similarity with the earlier reports of Naik *et al.* (1994), Lokapur (1997) and Pawar (2000) who noticed that hybrids recorded negative heterosis over better parent. Kanaka (1979), Atkins (1979), Rao *et al.* (1993), Biradar (1995) and Ganesh *et al.* (1996) also found that the hybrids came to flowering earlier than their parents. However, in the present investigation, all the crosses exhibited significant positive heterosis over standard check across the seasons, since none of the crosses were earlier to flower than the check. Indi and Goud (1981), Desai *et al*. (1985), Kide *et al*. (1985), Shivanna and Patil (1988) and Belavatagi (1997) reported positive heterosis over mid-parent, while Rao *et al.* (1976), Pandit (1989), Senthil and

Palaniswamy (1993), Badhe and Patil (1997) and Tiwari *et al.* (2003) documented positive heterosis over better parent.

4.2.2.3 100-Grain Weight (g): Heterosis over mid-parent for 100-grain weight ranged from 0.64 % (IS 2248 X PVK 801) to 39.42 % (IS 2248 X ICSB 56) in 2010, from -17.53 % (ICSB 56 X IS 2248) to 22.96 % (IS 2248 X PVK 801) in 2011 and from -0.36 % (PVK 801 X ICSB 56) to 25.86 % (IS 2248 X ICSB 56) across the seasons. IS 2248 X ICSB 56, IS 20843 X IS 2248, IS 20843 X PVK 801 and IS 2248 X IS 20843 recorded significant positive heterosis over mid-parent in 2010 and across the seasons. In addition to these crosses, ICSB 56 X IS 2248 exhibited significant positive heterosis in 2010. Only one cross (IS 2248 X PVK 801) exhibited significant positive heterosis in 2011. IS 2248 X ICSB 56 was highly heterotic to mid-parent among all crosses in 2010 and across the seasons. However, IS 2248 X PVK 801 recorded highest heterosis in 2011 and lowest heterosis in 2010, indicating high influence of environment on grain weight.

Heterosis over better parent had variation from -13.94 % (PVK 801 X IS 20843) to 28.42 % (IS 2248 X ICSB 56) in 2010, from -20.63 % (ICSB 56 X IS 2248) to 19.45 % (IS 2248 X PVK 801) in 2011 and from 8.36 % (IS 20843 X ICSB 56) to 38.18 % (IS 20843 X PVK 801) across the seasons. Five crosses (IS 20843 X PVK 801, IS 2248 X ICSB 56, IS 20843 X IS 2248, IS 2248 X IS 20843 and PVK 801 X IS 20843) across the seasons and IS 2248 X ICSB 56 in 2010 recorded significant positive heterosis over better parent. However, none of the crosses exhibited significant heterosis in 2011. IS 2248 X ICSB 56, IS 2248 X PVK 801 and IS 20843 X PVK 801 were highly superior to better parent in 2010, 2011 and across the seasons, respectively.

Heterosis over standard check varied from -12.87 % (ICSB 56 X IS 20843) to 35.20 % (IS 2248 X ICSB 56) in 2010, from -26.25 % (ICSB 56 X IS 2248) to 17.81 % (IS 2248 X PVK 801 and PVK 801 X IS 20843) in 2011 and from -7.06 % (IS 20843 X ICSB 56) to 20.44 % (PVK 801 X IS 2248) across the seasons. The crosses, IS 2248 X ICSB 56, PVK 801 X IS 2248 and IS 20843 X PVK 801 recorded significant positive heterosis over standard check in 2010. IS 2248 X ICSB 56 in 2010, IS 2248 X PVK 801 and PVK 801 X IS 20843 in 2011 and PVK 801 X IS 2248 across the seasons were highly heterotic over standard check.

Nearly 50 per cent of the hybrids exhibited significant positive heterosis over both mid-parent and better parent. Significant positive relative heterosis for the trait was also evidenced by Lokapur (1997). Limited heterosis was noticed by Shivanna

(1989), Rao *et al.* (1993) and Biradar (1995). Contrarily, a wide range of heterosis was reported by Rao (1970), Kanaka (1979), Desai *et al.* (1980), Desai *et al.* (1983), Shinde *et al.* (1983), Dinakar (1985) and Cabera and Miller (1985). Cross combination, IS 20843 X PVK 801 which gave the highest heterotic effect for 100-grain weight over better parent ranked second over the standard check across the seasons. IS 2248 X ICSB 56 showed highest heterosis over mid-parent, better parent and standard check in 2010, while, IS 2248 X PVK 801 recorded highest heterosis over mid-parent and better parent in 2011 and IS 20843 X PVK 801 exhibited maximum heterosis over better parent and second highest heterosis next to the PVK 801 X IS 2248 over standard check. Hence these crosses were identified to be the best in 2010, 2011 and across the seasons, respectively for this trait.

4.2.2.4 Grain Yield (t ha^{-1}): Grain yield is the complex quantitative character largely influenced either directly or indirectly by many component traits. Grain yield showed mid-parent heterosis in the range of -17.49 % (IS 2248 X PVK 801) to 164.99 % (IS 20843 X ICSB 56) in 2010, from -43.21 % (IS 2248 X ICSB 56) to 83.63 % (IS 20843 X ICSB 56) in 2011 and from -21.51 % (IS 2248 X PVK 801) to 129.56 % (ICSB 56 X IS 2248) across the seasons. More than 50 % of the hybrids recorded significant positive heterosis over mid-parent in both the seasons and across the seasons, while IS 2248 X PVK 801 consistently showed negative heterosis among all the crosses in both the seasons. IS 20843 X ICSB 56 in both seasons and ICSB 56 X IS 2248 across the seasons were highly heterotic for grain yield over mid-parent.

Heterosis over better parent varied from -30.90 % (IS 2248 X PVK 801) to 141.40 % (IS 20843 X ICSB 56) in 2010, from -46.88 % (IS 2248 X ICSB 56) to 45.51 % (IS 20843 X ICSB 56) in 2011 and from 8.38 % (PVK 801 X IS 20843) to 165.60 % (IS 20843 X ICSB 56) across the seasons. IS 20843 X ICSB 56 and its reciprocal cross showed significant positive heterosis consistently in both the seasons and across the seasons over better parent (IS 20843). One cross (IS 2248 X PVK 801) in 2010 and four crosses (IS 2248 X ICSB 56, IS 2248 X PVK 801, IS 20843 X IS 2248 and IS 2248 X IS 20843) in 2011 showed significant negative heterosis. Highest heterosis was recorded by IS 20843 X ICSB 56 in both the seasons and across the seasons over the better parent.

Heterosis over standard check ranged from 52.88 % (IS 2248 X PVK 801) to 192.04 % (ICSB 56 X PVK 801) in 2010, from -58.83 % (IS 2248 X ICSB 56) to 109.67 % (IS 20843 X PVK 801) in 2011 and from 6.07 % (IS 2248 X PVK 801) to 125.22 % (IS 20843 X PVK 801) across the seasons. All the crosses recorded significant positive heterosis over standard check in 2010. More than 50 per cent of the hybrids exhibited significant positive heterosis over standard check in 2011 and across the seasons. However, IS 2248 X ICSB 56, IS 2248 X PVK 801, IS 20843 X IS 2248 and IS 2248 X IS 20843 exhibited negative heterosis in 2011. ICSB 56 X PVK 801 in 2010 and IS 20843 X PVK 801 in 2011 and across the seasons were highly superior to standard check.

Most of the hybrids showed significant positive heterosis over mid-parent, better parent and standard check in both the seasons and across the seasons. Many earlier researchers recorded significantly greater magnitude of heterosis for grain yield in sorghum (Indi and Goud, 1981 and Karthik, 2004). IS 20843 X ICSB 56 was highly superior over better parent in both the seasons and across the seasons. Further, this cross ranked second over the standard check across the seasons with its *per se* performance closer to the high yielding hybrid *i.e.*, IS 20843 X PVK 801 developed in this study. IS 20843 X PVK 801 topped in heterotic effect over standard check with its highest *per se* performance among all crosses.

4.2.2.5 Grain Zinc (mg kg^{-1}): Heterosis over mid-parent ranged from -52.18 % (IS 2248 X ICSB 56) to 2.32 % (IS 20843 X IS 2248) in 2010, from -5.09 % (PVK 801 X ICSB 56) to 91.64 % (IS 2248 X PVK 801) in 2011 and from -28.77 % (ICSB 56 X PVK 801) to 28.23 % (IS 2248 X IS 20843) across the seasons. None of the crosses recorded significant positive heterosis in 2010. Fifty per cent of the hybrids (IS 2248 X PVK 801, PVK 801 X IS 2248, IS 2248 X ICSB 56, IS 2248 X IS 20843, IS 20843 X IS 2248 and ICSB 56 X IS 2248) exhibited significant positive heterosis in 2011, while IS 2248 X IS 20843 showed significant positive heterosis across the seasons. All the crosses involving PVK 801 as one of the parent and the cross, IS 2248 X ICSB 56 recorded significant negative heterosis in 2010. Due to seasonal effect, more than 50 % of the hybrids exhibited contrary results in 2010 and 2011. IS 20843 X IS 2248, IS 2248 X PVK 801 and IS 2248 X IS 20843 recorded the highest heterosis in 2010, 2011 and across the seasons, respectively. Across the seasons, only one cross, IS 2248 X IS 20843 (28.23 %) exhibited significant positive heterosis over its mid-parent (Fig 4.6).

Heterosis over better parent varied from -62.22 % (IS 2248 X ICSB 56) to -7.22 % (IS 20843 X IS 2248) in 2010, from -12.49 % (PVK 801 X IS 20843) to 77.80 % (IS 2248 X IS 20843) in 2011 and from -21.12 % (ICSB 56 X PVK 801) to 37.09 % (IS 2248 X IS 20843) across the seasons. None of the crosses exhibited positive heterosis over better parent in 2010. IS 2248 X IS 20843, IS 2248 X ICSB 56, IS 2248 X PVK 801, PVK 801 X IS 2248 and IS 20843 X IS 2248 recorded significant positive

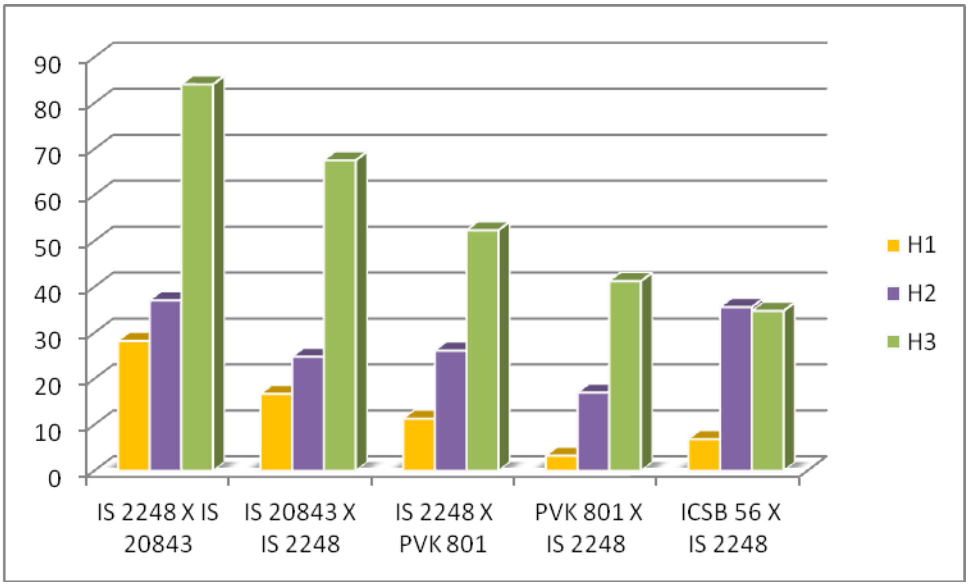

Figure 4.6. Heterosis over mid-parent, better parent and standard check exhibited by promising hybrids for grain zinc across the seasons

H1: Heterosis over mid-parent; **H2: Heterosis over better parent;**

H3: Heterosis over standard check

heterosis in 2011, while IS 2248 X IS 20843, ICSB 56 X IS 2248, IS 2248 X PVK 801 and IS 20843 X IS 2248 exhibited significant positive heterosis across the seasons. Almost all the crosses recorded significant negative heterosis over better parent except IS 2248 X IS 20843 and its reciprocal cross in 2010. IS 2248 X IS 20843 had consistently high heterosis in both the seasons and across the seasons when compared to all the remaining crosses.

Heterosis over standard check varied from -25.03 % (IS 2248 X ICSB 56) to % (IS 2248 X IS 20843) in 2011 and from -21.61 % (ICSB 56 X PVK 801) to 84.08 %(IS 2248 X IS 20843) across the seasons. IS 20843 X IS 2248, IS 2248 X IS 20843 and ICSB 56 X IS 2248 showed significant positive heterosis over standard check in both the seasons. Besides these crosses, IS 2248 X PVK 801, IS 2248 X ICSB 56 and PVK 801 X IS 2248 exhibited significant positive heterosis in 2011. IS 2248 X IS 20843, IS 20843 X IS 2248, IS 2248 X PVK 801, PVK 801 X IS 2248 and ICSB 56 X IS 2248 showed significant heterosis in positive direction across the seasons (Fig 4.7). None of the crosses recorded significant negative heterosis over standard check in both the seasons and across the seasons. IS 20843 X IS 2248 in 2010 and IS 2248 X IS 20843 in 2011 and across the seasons showed highest heterotic effect over standard check.

IS 2248 X IS 20843 was highly heterotic in grain zinc since it showed highest heterosis over better parent and standard check across the seasons. Even though most of the hybrids were positively heterotic, only few (<50 %) hybrids showed significant heterosis. Similar results were reported by Velu (2006) and Rai *et al*. (2007) in pearl millet and Chakraborti *et al*. (2009) in maize. These results indicated that there would be a little opportunity to exploit heterosis for grain zinc. Most of the crosses that recorded negative heterosis in 2010 showed positive heterosis in 2011 indicating high influence of environment on the grain zinc content.

4.2.3 Combining Ability Analysis

4.2.3.1 Analysis of Variance for Combining Ability

The analysis of variance for combining ability (Tables 4.31 and 4.32) revealed that the mean sum of squares due to GCA of parents and SCA of crosses were significant for all the characters in 2010, while mean sum of squares due to GCA of parents and SCA of crosses were significant for all the characters except days to 50 % flowering in 2011. The mean sum of squares due to reciprocal crosses was consistently significant for grain yield and grain zinc in both the seasons. In addition to these

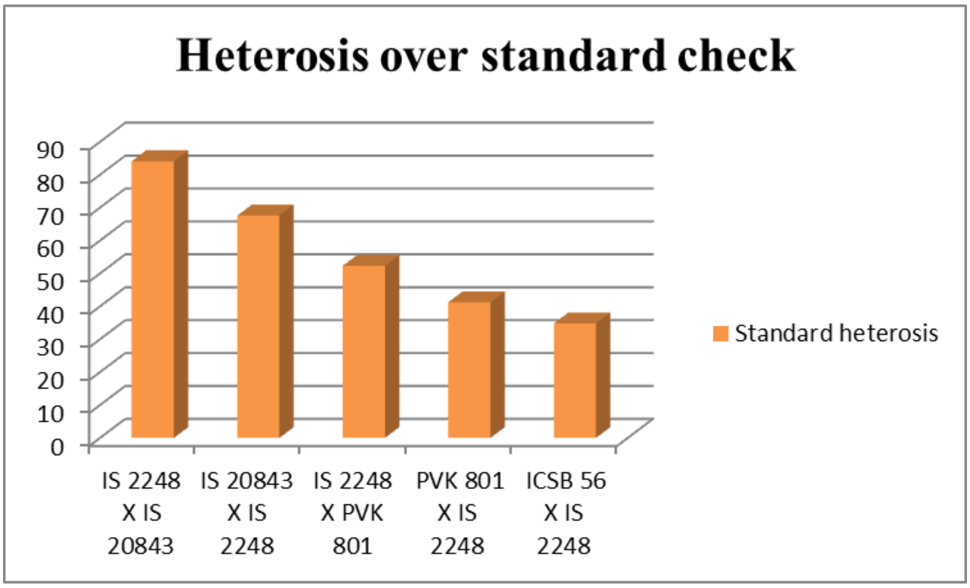

Figure 4.7. Heterosis over standard check exhibited by promising hybrids for grain zinc across the seasons

Table 4.31. Analysis of variance for combining ability estimates for various agronomic characters and grain zinc content of parents in sorghum during *postrainy* season, 2010

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain zinc (mg Kg^{-1})
GCA	3	0.35**	22.95**	0.74**	1.70**	274.33**
SCA	6	0.13**	31.21**	0.26**	5.54**	124.50**
Reciprocal	6	0.00	5.24**	0.08	1.30**	36.89**
Error	30	0.01	0.16	0.06	0.25	10.46
GCA variance		0.04	2.85	0.09	0.18	32.98
SCA variance		0.12	31.05	0.2	5.29	114.04
GCA/ SCA		0.33	0.09	0.45	0.03	0.29
Predictability ratio		0.4	0.16	0.47	0.06	0.37

* indicates significance @ 5 % level of probability;

** indicates significance @ 1 % level of probability

Table 4.32. Analysis of variance for combining ability estimates for various agronomic characters and grain zinc content in sorghum during *postrainy* season, 2011

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain zinc (mg Kg^{-1})
GCA	3	0.33**	1.16	0.44**	11.49**	380.98**
SCA	6	0.19**	0.38	0.13	2.18**	170.06**
Reciprocal	6	0.01	0.22	0.09	0.76**	28.83**
Error	30	0.01	1.17	0.08	0.09	7.29
GCA variance		0.04	-0.00	0.05	1.43	46.71
SCA variance		0.18	-0.79	0.05	2.09	162.77
GCA/ SCA		0.22	0.00	1	0.68	0.29
Predictability ratio		0.31	0.00	0.67	0.58	0.36

* indicates significance @ 5 % level of probability;

** indicates significance @ 1 % level of probability

characters, days to 50 % flowering and grain iron showed significant variation for reciprocal crosses in 2010.

The pooled analysis of variance (Table 4.33) across the seasons for combining ability indicated that the mean sum of squares due to GCA, SCA and reciprocal crosses were highly significant for all the characters except the mean sum of squares due to reciprocal crosses for plant height and grain zinc.

The variance due to SCA was more than the variance due to GCA for almost all the characters except 100-grain weight in both the seasons, indicating the predominance of non-additive gene effect in controlling the expression of these traits. The variances due to GCA and SCA revealed that 100-grain weight was governed by non-additive gene action in 2010, while both non-additive and additive gene actions in 2011.

4.2.3.2 *gca, sca* and Reciprocal Effects: The *gca, sca* and reciprocal effects are presented in Tables 4.34 and 4.35 and are discussed hereunder.

4.2.3.2.1 Plant Height (m): Plant height significantly varied among parents and direct crosses but not among reciprocal crosses, consistently in both the seasons and across the seasons. SCA variance was higher than the GCA variance suggesting the presence of non-additive gene action for this trait, consistently in individual seasons and across the seasons, which was in true with the results of low predictability ratio (0.37) across the seasons. These results were in agreement with the reports of Berenji (1988), Iyanar *et al*. (2001) and Umakanth *et al*. (2002). Interestingly, importance of additive gene action for this trait was reported by Borikar and Bhale (1982), Nayakar (1985), Chandrashekharappa (1987), Shivanna and Patil (1988), Sakhare *et al.* (1992), Shivanna *et al.* (1992) and Senthil and Palaniswamy (1994), while both additive and non-additive type of gene action was reported by Rao and Goud (1977), Giriraj and Goud (1983), Dabholkar and Lal (1987), Dinakar (1985), Sahib and Reddy (1986) and Chand (1996) for this character.

Plant height ranged in *gca* effects from -0.28 (ICSB 56) to 0.17 (IS 20843) in 2010, from -0.23 (ICSB 56) to 0.26 (IS 20843) in 2011 and from -0.25 (ICSB 56) to 0.21 (IS 20843) across the seasons for parents. IS 20843 followed by IS 2248 and ICSB 56 followed by PVK 801 recorded highest significant positive and negative *gca* effects, respectively in both the seasons and across the seasons. Among all four parents, IS 2248 and PVK 801 showed non-significant *gca* effects in 2011 and 2010, respectively. High positive and negative *gca* effects are desirable for increasing and decreasing the plant height, respectively.

Table 4.33. Pooled analysis of variance for combining ability estimates for various agronomic characters and grain zinc content in sorghum

Source of variation	Degrees of freedom	Mean sum of squares				
		Plant height (m)	Days to 50 % flowering	100-grain weight (g)	Grain yield (t ha^{-1})	Grain zinc (mg Kg^{-1})
GCA	3	0.66**	19.85**	0.62**	26.57**	603.36**
SCA	6	0.27**	29.72**	0.25**	12.54**	81.63**
Reciprocal	6	0.01	5.35**	0.10*	1.50**	9.06
Error	60	0.00	0.17	0.03	0.17	4.44
GCA variance		0.08	2.46	0.07	3.3	74.87
SCA variance		0.27	29.55	0.22	12.37	77.19
GCA/ SCA		0.30	0.08	0.32	0.27	0.97
Predictability ratio		0.37	0.14	0.39	0.35	0.66

* indicates significance @ 5 % level of probability;
** indicates significance @ 1 % level of probability

Table 4.34. Estimates of general and specific combining ability effects for plant height, days to 50 % flowering and 100-grain weight in sorghum in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Plant height (m)			Days to 50 % flowering			100 grain weight (g)		
	2010	2011	POOLED	2010	2011	POOLED	2010	2011	POOLED
***gca* effects**									
IS 2248	0.15**	0.05	0.10**	-1.25**	0.10	-0.86**	0.26**	0.04	0.15**
IS 20843	0.17**	0.26**	0.21**	2.50**	-0.56	1.63**	-0.36**	0.19*	-0.09*
PVK 801	-0.03	-0.08**	-0.06**	-0.71**	0.27	-0.43**	0.24**	0.11	0.18**
ICSB 56	-0.28**	-0.23**	-0.25**	-0.54**	0.19	-0.34**	-0.13	-0.34**	-0.24**
S.E (parents)	0.03	0.03	0.01	0.12	0.33	0.09	0.08	0.08	0.04
***sca* effects**									
IS 2248 X IS 20843	-0.07	0.11*	0.02	-2.42**	0.31	-1.64**	0.32*	0.16	0.24**
IS 2248 X PVK 801	0.12*	0.20**	0.16**	-0.38	-0.19	-0.32*	-0.12	0.29	0.08
IS 2248 X ICSB 56	0.17**	0.23**	0.20**	1.13**	-0.10	0.78**	0.44**	-0.14	0.15*
IS 20843 X PVK 801	0.11*	0.17**	0.14**	-3.29**	0.15	-2.31**	0.26	0.15	0.21**
IS 20843 X ICSB 56	-0.00	0.18**	0.09**	-4.13**	0.56	-2.80**	-0.15	0.08	-0.03
PVK 801 X ICSB 56	0.27**	0.00	0.14**	0.42	-0.27	0.23	0.06	-0.15	-0.05
S.E (Direct crosses)	0.05	0.05	0.03	0.23	0.60	0.16	0.14	0.15	0.07

Table 4.34. (Contd.)

Genotype	Plant height (m)			Days to 50 % flowering			100 grain weight (g)		
	2010	2011	POOLED	2010	2011	POOLED	2010	2011	POOLED
Reciprocal effects									
IS 20843 X IS 2248	0.02	-0.08	-0.03	0.00	0.33	0.09	-0.04	0.00	-0.02
PVK 801 X IS 2248	0.03	0.00	0.02	3.50**	0.00	2.50**	-0.27	0.11	-0.08
PVK 801 X IS 20843	-0.02	-0.05	-0.03	-1.00**	0.33	-0.63**	0.36*	-0.09	0.13
ICSB 56 X IS 2248	0.03	0.02	0.03	1.50**	0.00	1.07**	0.23	0.42*	0.32**
ICSB 56 X IS 20843	-0.08	0.05	-0.02	0.33	0.00	0.24	0.02	-0.04	-0.01
ICSB 56 X PVK 801	0.05	0.10	0.07*	-0.33	-0.67	-0.42*	0.00	-0.24	-0.12
S.E (Reciprocal crosses)	0.06	0.07	0.03	0.29	0.76	0.20	0.17	0.19	0.09

* indicates significance @ 5 % level of probability; ** indicates significance @ 1 % level of probability

Table 4.35. Estimates of general and specific combining ability effects for grain yield and grain zinc in sorghum in *postrainy* seasons, 2010, 2011 and pooled data

Genotype	Grain yield (t ha^{-1})			Grain zinc (mg kg^{-1})		
	2010	2011	POOLED	2010	2011	POOLED
***gca* effects**						
IS 2248	-0.43**	-1.60**	-1.76**	5.99**	9.96**	7.97**
IS 20843	-0.33*	0.92**	0.68**	3.56**	-0.71	1.42**
PVK 801	0.56**	0.92**	1.19**	-2.69**	-4.11**	-3.40**
ICSB 56	0.20	-0.24**	-0.11	-6.86**	-5.14**	-6.00**
S.E (parents)	0.15	0.09	0.09	0.99	0.83	0.46
***sca* effects**						
IS 2248 X IS 20843	0.31	-0.57**	-0.35*	5.14**	6.50**	5.82**
IS 2248 X PVK 801	-0.93**	-0.20	-0.73**	-7.15**	11.06**	1.96*
IS 2248 X ICSB 56	1.41**	-0.23	0.60**	-6.22**	5.86**	-0.18
IS 20843 X PVK 801	0.49	0.97**	1.20**	-6.56**	-2.54	-4.55**
IS 20843 X ICSB 56	1.41**	1.30**	2.05**	-0.74	-1.72	-1.23
PVK 801 X ICSB 56	1.03**	0.28	0.87**	-2.34	-3.56*	-2.95**
S.E (Direct crosses)	0.28	0.17	0.16	1.81	1.51	0.83
Reciprocal effects						
IS 20843 X IS 2248	0.22	0.20	0.32	-1.28	6.22**	2.47*
PVK 801 X IS 2248	-0.75*	-0.81**	-1.19**	2.98	0.32	1.65
PVK 801 X IS 20843	0.82*	0.09	0.57**	1.37	0.38	0.88
ICSB 56 X IS 2248	1.28**	-1.07**	-0.26	-9.20**	6.88**	-1.16
ICSB 56 X IS 20843	0.48	0.32	0.58**	-0.95	0.00	-0.47
ICSB 56 X PVK 801	-0.86*	0.58**	0.05	3.57	-0.43	1.57
S.E (Reciprocal crosses)	0.35	0.22	0.20	2.29	1.91	1.05

* indicates significance @ 5 % level of probability;

** indicates significance @ 1 % level of probability

Direct crosses varied for *sca* effects from -0.07 (IS 2248 X IS 20843) to 0.27 (PVK 801 X ICSB 56) in 2010, from 0.00 (PVK 801 X ICSB 56) to 0.23 (IS 2248 X ICSB 56) in 2011 and from 0.02 (IS 2248 X IS 20843) to 0.20 (IS 2248 X ICSB 56) across the seasons. PVK 801 X ICSB 56 followed by IS 2248 X ICSB 56 in 2010, IS 2248 X ICSB 56 followed by IS 2248 X PVK 801 in 2011 and across the seasons recorded highest positive significant *sca* effects. Most of the crosses exhibited significant positive *sca* effects in both the seasons and across the seasons. IS 2248 X PVK 801, IS 2248 X ICSB 56 and IS 20843 X PVK 801 recorded significant positive *sca* effects consistently in both the seasons and across the seasons. All these crosses had only one parent with positive *gca* effect. Among all the direct crosses, only one cross (IS 2248 X IS 20843) showed negative *sca* effect in 2010, suggesting that all the crosses resulted in tallness. None of the crosses showed significant negative *sca* effects in both the seasons and across the seasons.

Reciprocal effects ranged from -0.08 (ICSB 56 X IS 20843) to 0.05 (ICSB 56 X PVK 801) in 2010, from -0.08 (IS 20843 X IS 2248) to 0.10 (ICSB 56 X PVK 801) in 2011 and from -0.03 (IS 20843 X IS 2248 and PVK 801 X IS 20843) to 0.07 (ICSB 56 X PVK 801) across the seasons. ICSB 56 X PVK 801 followed by ICSB 56 X IS 2248 in 2010 and across the seasons and ICSB 56 X PVK 801 followed by ICSB 56 X IS 20843 in 2011 recorded highest positive reciprocal effects. ICSB 56 X IS 20843 in 2010 and IS 20843 X IS 2248 in 2011 and across the seasons showed highest negative reciprocal effects among all the reciprocal crosses. Apart from these crosses, PVK 801 X IS 20843 also recorded the highest negative reciprocal effect across the seasons. None of the crosses recorded significant reciprocal effects except ICSB 56 X PVK 801 across the seasons. IS 2248 X ICSB 56 was found to be the best cross with the highest positive *sca* effects across the seasons with the involvement of good x poor general combiners as its parents indicating the necessity of parents with high *gca* effects to explore good *sca* effect in the cross.

4.2.3.2.2 Days to 50 % Flowering: Both parents and crosses revealed significant variation for days to 50 % flowering in 2010 and across the seasons, but not in 2011. The ratio of GCA variance to SCA variance was low, suggesting that this trait was predominantly governed by non-additive gene action. Low predictability ratio (0.14) obtained for this trait suggested the predominant role of non-additive gene action in controlling this trait. Since, non-additive gene action was found to be governing this trait, breeding methods involving selection, intermating among the selected ones and reselection may help to improve this trait besides exploitation of heterosis breeding.

Conformity results were reported by Kide *et al.* (1985), Shivanna (1989), Naik *et al.* (1994), Belavatagi (1997), Biradar (1995) and Kanawade *et al.* (2001). Contrarily, importance of additive gene action for days to 50% flowering was reported by Nayakar (1985), Dabholkar and Usha (1988), Shivanna *et al.* (1992), Senthil and Palaniswamy (1994) and Siddiqui and Baig (2001), while Kanaka (1979) and Patel *et al.* (1995) found the importance of both additive and non-additive components of genetic variances for days to 50 per cent flowering.

gca effects ranged from -1.25 (IS 2248) to 2.50 (IS 20843) in 2010, from -0.56 (IS 20843) to 0.27 (PVK 801) in 2011 and from -0.86 (IS 2248) to 1.63 (IS 20843) across the seasons. Contrasting results were obtained for this trait in both the seasons due to environmental influence. IS 2248 followed by PVK 801 in 2010 and across the seasons, while IS 20843 in 2011 showed highest negative *gca* effects. These parents can thus be used as good combiners in crossing programmes. Highest positive *gca* effects were exhibited by IS 20843 in 2010 and across the seasons and PVK 801 in 2011.

Direct crosses varied for *sca* effects from -4.13 (IS 20843 X ICSB 56) to 1.13 (IS 2248 X ICSB 56) in 2010, from -0.27 (PVK 801 X ICSB 56) to 0.56 (IS 20843 X ICSB 56) in 2011 and from -2.80 (IS 20843 X ICSB 56) to 0.78 (IS 2248 X ICSB 56) across the seasons. IS 20843 X ICSB 56 followed by IS 20843 X PVK 801 in 2010 and across the seasons and PVK 801 X ICSB 56 followed by IS 2248 X PVK 801 in 2011 recorded highest negative *sca* effects with one of its parents with high negative *gca* effects.

Reciprocal effects ranged from -1.00 (PVK 801 X IS 20843) to 3.50 (PVK 801 X IS 2248) in 2010, from -0.67 (ICSB 56 X PVK 801) to 0.33 (IS 20843 X IS 2248 and PVK 801 X IS 20843) in 2011 and from -0.63 (PVK 801 X IS 20843) to 2.50 (PVK 801 X IS 2248) across the seasons. PVK 801 X IS 20843 followed by ICSB 56 X PVK 801 in 2010 and across the seasons and ICSB 56 X PVK 801 in 2011 recorded highest negative reciprocal effects. Significant positive reciprocal effects were exhibited by PVK 801 X IS 2248 and ICSB 56 X IS 2248 in 2010 and across the seasons. IS 20843 X ICSB 56 could be regarded as the best hybrid with high negative significant *sca* effect among twelve crosses across the seasons, which resulted due to the involvement of good general combiner as one of its parents, while the other parent was a poor general combiner. The interaction between the favourable alleles from both the parents might result in cross with high *sca* effects. Selection, intermating among the selected ones and reselection might be helpful to improve this trait besides exploitation of heterosis breeding because of the importance of non-additive gene action for this trait.

4.2.3.2.3 100-Grain Weight (g): Significant variation was observed among the parents for 100-grain weight in both the seasons and across the seasons, while only direct crosses in 2010 and both direct and reciprocal crosses across the seasons recorded significant variation. 100-grain weight was governed by non-additive gene action since GCA variance was lower than the SCA variance and also due to its lower predictability ratio (0.39) across the seasons. These results were in line with the reports of Patil and Thombre (1984), Shivanna (1989) and Patel *et al*. (1990), while the importance of additive gene action for this trait was reported by Nayakar (1985), Dabholkar and Usha (1988), Jagadishwar and Shinde (1992) and Shivanna *et al*. (1992). However, GCA variance was equal to SCA variance in 2011, suggesting equal importance of both additive and non-additive gene actions in governing this trait.

Parents varied in *gca* effects for 100-grain weight from -0.36 (IS 20843) to 0.26 (IS 2248) in 2010, from -0.34 (ICSB 56) to 0.19 (IS 20843) in 2011 and from -0.24 (ICSB 56) to 0.18 (PVK 801) across the seasons. IS 2248 followed by PVK 801 in 2010, IS 20843 in 2011 and PVK 801 followed by IS 2248 across the seasons recorded highest significant positive *gca* effects, while significant negative *gca* effects were exhibited by IS 20843 in 2010, ICSB 56 in 2011 and IS 20843 followed by ICSB 56 across the seasons. PVK 801, which exhibited high positive significant *gca* effect across the seasons, could be considered as the best parent among the parents with more grain weight.

Wide variation of *sca* effects ranging from -0.15 (IS 20843 X ICSB 56) to 0.44 (IS 2248 X ICSB 56) in 2010, from -0.15 (PVK 801 X ICSB 56) to 0.29 (IS 2248 X PVK 801) in 2011 and from -0.05 (PVK 801 X ICSB 56) to 0.24 (IS 2248 X IS 20843) across the seasons. The crosses, IS 2248 X ICSB 56 followed by IS 2248 X IS 20843 in 2010 and IS 2248 X IS 20843 followed by IS 20843 X PVK 801 across the seasons exhibited highest significant positive *sca* effects with one of their parents as good general combiner. None of the crosses recorded significant negative *sca* effects in both the seasons and across the seasons.

Reciprocal effects ranged from -0.27 (PVK 801 X IS 2248) to 0.36 (PVK 801 X IS 20843) in 2010, from -0.24 (ICSB 56 X PVK 801) to 0.42 (ICSB 56 X IS 2248) in 2011 and from -0.12 (ICSB 56 X PVK 801) to 0.32 (ICSB 56 X IS 2248) across the seasons. Significant positive reciprocal effects were recorded by PVK 801 X IS 20843 in 2010 and ICSB 56 X IS 2248 in 2011 and across the seasons. Out of the twelve crosses, ICSB 56 X IS 2248 could be considered as the best cross with high positive significant *sca* effect across the seasons. ICSB 56 X IS 2248 was superior to all the other crosses with highest positive *sca* effect in respect of grain weight. Though, it was the result of crossing between poor and good general combiners, its high performance might be due to the interaction of favourable alleles from both of its parents. Selection, intermating among the parents and reselection might be useful to further improve the grain weight.

4.2.3.2.4 Grain Yield (t ha^{-1}): Both parents and crosses varied significantly for grain yield in both the seasons and across the seasons. Predominantly, non-additive gene action was governing this trait, since GCA variance was lower than SCA variance in individual seasons and across the seasons, which was further strongly supported by the lower value of predictability ratio (0.35). Similar trend of results were reported by Rao and Goud (1977), Wilson *et al.* (1978), Patil and Thombre (1984), Kishan and Borikar (1988), Shivanna (1989), Armugam *et al.* (1995) and Siddiqui and Baig (2001). Contrary results were obtained by Palaniswamy and Subramanian (1986), Senthil and Palaniswamy (1994) and Iyanar *et al.* (2001), whereas, Ross *et al.* (1983), Dinakar (1985), Dabholkar and Usha (1988), Swarnalatha and Rana (1988), Patel *et al.* (1990), Jagadishwar and Shinde (1992), Sakhare *et al.* (1992), Shivanna *et al.* (1992), Rao *et al.* (1994) and Naik *et al.* (1994) opined that both GCA and SCA variances were important for grain yield.

Grain yield significantly varied in *gca* effects from -0.43 (IS 2248) to 0.56 (PVK 801) in 2010, from -1.60 (IS 2248) to 0.92 (IS 20843 and PVK 801) in 2011 and from -1.76 (IS 2248) to 1.19 (PVK 801) across the seasons. PVK 801 consistently recorded highest significant positive *gca* effect in both the seasons and across the seasons with its highest *per se* performance among the parents. Hence, it could be considered as the best parent for grain yield. In addition to PVK 801, IS 20843 exhibited significant positive *gca* effect in 2011 and across the seasons. Highest significant negative *gca* effects were recorded by IS 2248 consistently in both the seasons and across the seasons.

sca effects varied from -0.93 (IS 2248 X PVK 801) to 1.41 (IS 2248 X ICSB 56 and IS 20843 X ICSB 56) in 2010, from -0.57 (IS 2248 X IS 20843) to 1.30 (IS 20843 X ICSB 56) in 2011 and from -0.73 (IS 2248 X PVK 801) to 2.05 (IS 20843 X ICSB 56) across the seasons. IS 20843 X ICSB 56 consistently had highest significant positive *sca* effect in both the seasons and across the seasons and hence it can be suggested as the best cross among the twelve crosses. Besides this cross, IS 2248

X ICSB 56 and PVK 801 X ICSB 56 in 2010 and across the seasons and IS 20843 X PVK 801 in 2011 and across the seasons exhibited significant positive *sca* effects. IS 2248 X PVK 801 in 2010 and across the seasons and IS 2248 X IS 20843 in 2011 recorded highest negative *sca* effects.

Reciprocal effects ranged from -0.86 (ICSB 56 X PVK 801) to 1.28 (ICSB 56 X IS 2248) in 2010, from -1.07 (ICSB 56 X IS 2248) to 0.58 (ICSB 56 X PVK 801) in 2011 and from -1.19 (PVK 801 X IS 2248) to 0.58 (ICSB 56 X IS 20843) across the seasons. Season had great influence on grain yield since, the cross that recorded positive *sca* effect in one season showed negative *sca* effect in the other season. ICSB 56 X IS 2248 followed by PVK 801 X IS 20843 in 2010, ICSB 56 X PVK 801 in 2011 and ICSB 56 X IS 20843 followed by PVK 801 X IS 20843 across the seasons recorded high significant and positive reciprocal effects. All the crosses that showed highest significant positive reciprocal effects had one parent with good combining ability. Highest significant negative reciprocal effects were exhibited by ICSB 56 X PVK 801, ICSB 56 X IS 2248 and PVK 801 X IS 2248 in 2010, 2011 and across the seasons, respectively. IS 20843 X ICSB 56 was identified to be the best cross in respect of grain yield with positive *sca* effects with the involvement of a good general combiner as one of the parent and a poor general combiner as the other, indicating the necessity of at least one of the parents with good *gca* to get good *sca* in the hybrid. Since, non-additive gene action was found to be governing the trait, hybridization followed by selection, biparental mating in F_2 followed by single plant selection would facilitate the improvement of grain yield besides heterosis breeding.

4.2.3.2.5 Grain Zinc (mg kg^{-1}): Significant variation was observed among the parents and crosses for grain zinc in both the seasons and across the seasons. However, reciprocal crosses did not show significant variation across the seasons. SCA variance was slightly higher than the GCA variance across the seasons, suggesting that this trait was governed by non-additive gene action. However, predictability ratio (0.66) obtained indicated the predominant role of additive gene action with little role of non-additive gene action in governing this trait. This result was in conformity with the report of Majumdar *et al*. (1990). Additive gene action for this trait was reported by Velu (2006), Rai *et al*. (2007), Velu *et al*. (2011), Zhang *et al*. (2000), Gregorio (2002) and Gregorio and Htut (2003) and non-additive gene action for this trait was reported by Aruselvi *et al*. (2009) and Zhang *et al*. (1996).

gca effects ranged from -6.86 (ICSB 56) to 5.99 (IS 2248) in 2010, from -5.14 (ICSB 56) to 9.96 (IS 2248) in 2011 and from -6.00 (ICSB 56) to 7.97 (IS 2248) across the seasons. IS 2248 followed by IS 20843 consistently had significant positive *gca* effects in both the seasons and across the seasons. However, the *gca* effect of IS 20843 which was significantly positive in 2010, was found to be negative and non-significant in 2011. Significant negative *gca* effects were recorded by ICSB 56 followed by PVK 801 consistently in individual seasons and across the seasons. Among the parents, IS 2248 was the best parent since, it showed high positive significant *gca* effect consistently in both the seasons and across the seasons.

Direct crosses varied significantly in *sca* effects from -7.15 (IS 2248 X PVK 801) to 5.14 (IS 2248 X IS 20843) in 2010, from -3.56 (PVK 801 X ICSB 56) to 11.06 (IS 2248 X PVK 801) in 2011 and from -4.55 (IS 20843 X PVK 801) to 5.82 (IS 2248 X IS 20843) across the seasons. IS 2248 X IS 20843 in 2010, IS 2248 X PVK 801 followed by IS 2248 X IS 20843 and IS 2248 X ICSB 56 in 2011 and IS 2248 X IS 20843 followed by IS 2248 X PVK 801 across the seasons recorded high significant positive *sca* effects. All these crosses had only one parent as good combiner except IS 2248 X IS 20843 in 2010 and across the seasons which was the result of good x good combiner. IS 2248 X PVK 801, PVK 801 X ICSB 56 and IS 20843 X PVK 801 exhibited highest significant negative *sca* effects in 2010, 2011 and across the seasons, respectively.

Reciprocal effects ranged from -9.20 (ICSB 56 X IS 2248) to 3.57 (ICSB 56 X PVK 801) in 2010, from -0.43 (ICSB 56 X PVK 801) to 6.88 (ICSB 56 X IS 2248) in 2011 and from -1.16 (ICSB 56 X IS 2248) to 2.47 (IS 20843 X IS 2248) across the seasons. ICSB 56 X IS 2248 (poor x poor) followed by IS 20843 X IS 2248 (poor x good) in 2011 and IS 20843 X IS 2248 (good x good) across the seasons recorded significant positive reciprocal effects. The superiority of poor x poor combinations (ICSB 56 X IS 2248) might be due to the concentration and interaction between favourable genes contributed by the parents, while none of the reciprocal crosses exhibited significant negative effects. Out of the twelve crosses, IS 2248 X IS 20843 was the best cross with high positive significant *sca* effect across the seasons (Fig 4.8). Both the parents involved in the development of this cross were found to be good general combiners. The high frequency of dominant alleles from both the parents would result in the hybrid with high positive *sca* effect. This holds good when a trait is governed by additive gene action. As additive gene action predominates in controlling grain zinc, improvement of this trait can be done through hybridization followed by simple selection through pedigree method of breeding.

4.2.4 Character Association

These results are presented in Table 4.36 and are discussed hereunder.

4.2.4.1 Grain zinc with all the agronomic characters: Days to 50 % flowering (r = 0.226) followed by plant height (r = 0.092) in 2010, while plant height (r = 0.439) followed by 100-grain weight (r = 0.271) showed highest positive correlation with grain zinc in 2010 and 2011, respectively. Grain zinc had significant negative association with grain yield in both the seasons consistently. It had positive but non-significant association (r = 0.092) and positive significant association with plant height (r = 0.439) in 2010 and 2011, respectively. Days to 50 % flowering and 100-grain weight showed contrary results with grain zinc in both seasons indicating the environmental effect on the expression of grain zinc with these characters.

4.2.4.2 Correlation among all the agronomic characters: Highest significant and positive association was observed for 100-grain weight with grain yield (r = 0.390) and plant height (r = 0.503) in 2010 and 2011, respectively, while positive but non-significant correlations were observed for plant height with 100-grain weight (r = 0.184) followed by grain yield (r = 0.128) and days to 50 % flowering (r = 0.020) in 2010 and for grain yield with plant height (r = 0.257) followed by 100-grain weight (r =0.075) and days to 50 % flowering (r = 0.002) in 2011. Days to 50 % flowering showed significant negative correlation with 100-grain weight (r = -0.498) followed by grain yield (r = -0.447) in 2010, while negative but non-significant correlation with 100-grain weight (r = -0.135) followed by plant height (r = -0.034) in 2011. These results suggested that there was less possibility to develop the hybrids with all desirable characters. However, Liang *et al*. (1969), Patel *et al*. (1980) and Haris *et al*. (2001) observed significant positive correlation for days to 50 % flowering with grain yield. Patel *et al*. (1994) also observed the similar results by reporting negative correlation of days to 50 % flowering with grain yield. These results indicated that there is a limited scope to develop the early varieties with large grain size.

4.2.5 Path Co-efficient Analysis

Direct and indirect effects of various characters on grain zinc are presented in Tables 4.37 and 4.38 and are discussed hereunder.

4.2.5.1 During *postrainy* season, 2010: Plant height (0.083) followed by days to 50 % flowering (0.019) and 100-grain weight (0.008) showed highest positive direct effects on grain zinc, while grain yield had negative direct effect (-0.396) on grain zinc among all the characters and also highest negative association with grain zinc. Its negative association with grain zinc (r =-0.418) was mainly due to its negative direct

Table 4.36. Phenotypic and genotypic correlation co-efficient matrix of grain zinc content with various agronomic traits during *postrainy* seasons, 2010 and 2011

Character	Plant height (m)	Days to 50 % flowering	Plant aspect score	100-grain weight (g)	Grain yield (t ha^{-1})	Grain zinc (mg kg^{-1})
Plant height (m)	1.000	0.020 (0.006)	0.378** (0.835**)	0.184 (0.244)	0.128 (0.168)	0.092 (0.139)
Days to 50 % flowering	-0.034 (0.350*)	1.000	0.208 (0.476**)	-0.498** (-0.649**)	-0.447** (-0.497**)	0.226 (0.241)
Plant aspect score	-0.051 (0.014)	0.033 (0.204)	1.000	-0.239 (-0.583**)	-0.175 (-0.332*)	0.256 (0.653**)
100-grain weight (g)	0.503** (0.766**)	-0.135 (-0.131)	0.050 (0.247)	1.000	0.390** (0.590**)	-0.178 (-0.205)
Grain yield (t ha^{-1})	0.257 (0.273)	0.002 (0.095)	-0.587** (-0.749**)	0.075 (0.207)	1.000	-0.418** (-0.629**)
Grain zinc (mg kg^{-1})	0.439** (0.544**)	-0.012 (-0.004)	0.471** (0.596**)	0.272 (0.649**)	-0.538** (-0.617**)	1.000

'*' indicates significance at 5 % probability *i.e.*, r=>0.2845

'**' indicates significance at 1 % probability *i.e.*, r=>0.3683

Values in parenthesis indicates genotypic correlation co-efficients

Values above diagonal represent the correlations among various characters in *post-rainy* season, 2010 and below diagonal represent the correlations among various characters in *post-rainy* season, 2011

Table 4.37. Phenotypic path matrix showing direct and indirect effects of various agronomic traits on grain zinc during *postrainy* season, 2010

Character	Plant height (m)	Days to 50 % flowering	Plant aspect score	100-grain weight (g)	Grain yield (t ha^{-1})	Correlation with grain zinc
Plant height (m)	**0.083**	0.000	0.058	0.002	-0.051	0.092
Days to 50 % flowering	0.002	**0.019**	0.032	-0.004	0.177	0.226
Plant aspect ratio	0.031	0.004	**0.153**	-0.002	0.070	0.256
100-grain weight (g)	0.015	-0.010	-0.037	**0.008**	-0.155	-0.178
Grain yield (t ha^{-1})	0.011	-0.009	-0.027	0.003	**-0.396**	-0.418**

Residual effect = 0.886

Bold values in diagonal represents direct effects

Table 4.38. Phenotypic path matrix showing direct and indirect effects of various agronomic traits on grain zinc during *postrainy* season, 2011

Character	Plant height (m)	Days to 50 % flowering	Plant aspect score	100-grain weight (g)	Grain yield (t ha^{-1})	Correlation with grain zinc
Plant height (m)	**0.596**	-0.000	-0.007	0.006	-0.156	0.439**
Days to 50 % flowering	-0.020	**0.007**	0.005	-0.002	-0.001	-0.012
Plant aspect score	-0.030	0.000	**0.143**	0.001	0.357	0.471**
100-grain weight (g)	0.299	-0.001	0.007	**0.012**	-0.046	0.272
Gain yield (t ha^{-1})	0.153	0.000	-0.084	0.001	**-0.608**	-0.538**

Residual effect = 0.584

Bold values in diagonal represents direct effects

effect (-0.396) and also negative indirect effect through days to 50 % flowering (-0.009). This shows that increasing grain yield through selection may not necessarily lead to proportionate increase in grain zinc. Plant height was positively effected through 100-grain weight (0.002) followed by days to 50 % flowering (0.001), while negatively effected through grain yield (-0.051). Days to 50 % flowering was positively effected through grain yield (0.177) followed by plant height (0.002), while negatively effected through 100-grain weight (-0.004). 100-grain weight and grain yield had positive effect through plant height and negative effect through days to 50 % flowering. In addition to these effects, 100-grain weight showed negative effect through grain yield (-0.155), while grain yield showed positive effect through 100-grain weight (0.003) on grain zinc. Due to the high negative indirect effects *via* other characters, 100-grain weight showed negative correlation (r = -0.179) with its positive direct effect on grain zinc (0.008). In such a situation, direct selection for this trait should be practiced to reduce the undesirable indirect effect on grain zinc.

4.2.5.2 During *postrainy* season, 2011: Highest positive direct effects were exhibited by plant height (0.596) followed by 100-grain weight (0.012) and days to 50 % flowering (0.007), while negative direct effect was showed by grain yield (-0.608). Plant height and 100-grain weight had negative effects on grain zinc through grain yield followed by days to 50 % flowering. Though, days to 50 % flowering had positive direct effect (0.007) on grain zinc, it negatively affected grain zinc through plant height (-0.020) followed by100-grain weight (-0.002) and grain yield (-0.001). Contrastingly, grain yield directly influenced the grain zinc in negative direction, while positively effected *via* plant height followed by 100-grain weight and grain yield. Because of high negative effects *via* other characters, days to 50 % flowering showed negative correlation (r = -0.011), even though it had positive direct effect on grain zinc. As a whole, plant height was considered as desirable trait, while grain yield was undesirable character during selection for the enhancement of mineral nutrients in grain sorghum.

Plant height had positive direct effect on grain zinc in both the seasons, while negative direct effect was showed by grain yield, but grain yield showed positive indirect effect through 100-grain weight. Though, 100-grain weight had positive direct effect on grain zinc, it negatively influenced the grain zinc through days to 50 % flowering.

High residual effects were observed in both the experiments, when grain iron/zinc was considered as dependent character in both the seasons. It revealed that some more characters, which were closely associated with grain iron and zinc contents, need to be included in this study apart from the characters studied.

CHAPTER V

SUMMARY AND CONCLUSIONS

Chapter V

SUMMARY AND CONCLUSIONS

The research work entitled "Heterosis and combining ability studies for grain iron and zinc contents in grain sorghum (*Sorghum bicolor* (L.) Moench)" was carried out at the ICRISAT farm, Patancheru, Hyderabad in 4 x 4 full-diallel in two experiments using contrasting parents for grain iron in the first experiment and those for grain zinc in the second experiment with the aims of estimating the magnitude of heterosis, studying the nature of gene action and combining ability of parents and crosses, determining the correlation of grain iron and zinc contents with grain yield and other important traits and direct and indirect effects of these characters on grain iron and zinc contents in sorghum. In both the experiments, data were recorded for days to 50 % flowering on plot basis (*i.e.*, plants having fully exerted stigmas on the main panicles) and 100-grain weight was recorded on a sample of 100 randomly selected grains from each replication. Plant height was measured from five randomly selected plants from each plot. Plant aspect score was recorded on a 1 to 5 scale where 1 = most desirable and 5 = least desirable. Grain yield was measured on plot basis from all the panicles harvested and dried to 12 % moisture level. The panicles were harvested at maturity and the grain was threshed carefully without any contact with metal or dust to avoid contamination. The cleaned seeds of each genotype were used to measure the iron content with Oxford X-supreme 8000 model X-ray flourescence analyzer (XRF). Heterosis over mid-parent, better parent and standard check were calculated for twelve hybrids in both experiments. The combining ability in diallel analysis was worked out according to Method-I and Model-I (fixed effects model) suggested by Griffing (1956). Correlation coefficients were calculated at phenotypic level using the formulae suggested by Falconer (1981). The direct and indirect effects at phenotypic level were estimated by taking grain iron content as dependent variable, using path coefficient analysis as suggested by Wright (1921) and Dewey and Lu (1959).

During *postrainy* seasons, 2010-11 and 2011-12, four parental lines (IS 2263, IS 13211, IS 10305 and SPV 1359) and the resultant twelve crosses generated by crossing in full-diallel fashion along with standard check (ICSR 40) were evaluated in the first experiment in Randomized Block Design (RBD) with three replications. The pooled analysis of variance revealed the significant variation among genotypes, genotype x environment interaction and environment for all the five characters studied (plant height, days to 50 % flowering, 100-grain weight, grain yield and grain zinc) except 100-grain weight. Heterosis for grain iron varied from -9.07 % to 12.89 % over mid-parent, -14.72 % to 8.55 % over better parent and from -7.19 % to 30.57 % over standard check across the seasons. Heterosis was found to be non-significant over mid-parent and better parent for grain iron indicating that additive gene action had a predominant role in the inheritance of this trait. Most of the hybrids recorded significant heterosis over standard check. Barring few crosses, none of the hybrids outperformed significantly the parents that had high levels of grain iron indicating that there would be little opportunity, if any, to exploit heterosis for improving this trait.

The pooled analysis of variance for combining ability revealed significant differences among parents, direct crosses and reciprocal crosses revealing the existence of wider variability in the material under study for all the characters. However, direct crosses did not show significant variation for grain iron. The ratio of GCA/SCA variances revealed that additive gene action was predominant in the inheritance of all the characters studied barring days to 50 % flowering. Predictability ratio revealed that grain iron content was found to be governed by additive gene action indicating the need to improve the parents for developing high iron containing sorghum hybrids. IS 2263 and IS 13211 were found to be promising general combiners for grain iron based on *gca* effects and SPV 1359 X IS 13211, IS 10305 X IS 13211, IS 10305 X IS 2263, SPV 1359 X IS 2263 and IS 2263 X IS 13211 were found to be promising hybrids for grain iron based on *sca* effects. Correlation studies revealed that plant height showed positive association, while days to 50 % flowering had negative correlation with grain iron during *postrainy* season, 2010. Plant height, 100-grain weight and grain yield exhibited negative correlation, while days to 50 % flowering showed positive association with grain iron content in 2011. This difference in the association of traits might be attributed to the influence of environment on these traits. Path coefficient analysis studies revealed that plant height, days to 50 % flowering and 100-grain weight showed controversial direct effects on grain iron in two *postrainy* seasons due to environmental influence. Grain yield showed negative direct effect on grain iron content consistently in both the seasons. The higher magnitude of residual effect in both the seasons indicated that it might be necessary to include some more characters closely related with grain iron content.

In second experiment, four parental lines contrasting for grain zinc (IS 2248, IS 20843, PVK 801 and ICSB 56) were crossed among each other in full-diallel fashion and the resultant twelve crosses along with their parents and standard check (ICSR 40) were evaluated during *postrainy* seasons, 2010-11 and 2011-12 in Randomized Block Design (RBD) with three replications. Analysis of variance studies revealed that genotypes and genotype x environment interaction were significant for all the characters studied and environment was significant for plant height, days to 50 % flowering and grain yield. Heterosis for grain zinc ranged from -28.77 % to 28.23 % over mid-parent, from -21.12 % to 37.09 % over better parent and from -21.61 % to 84.08 % over standard check across the seasons. But majority of hybrids did not show significant heterosis over mid-parent, better parent and standard check suggesting that additive gene action governed the inheritance of this trait. Barring few crosses, none of the hybrids outperformed significantly the parents which had high level of grain zinc, indicating that there would be little opportunity, if any, to exploit heterosis for improving this trait.

The combined analysis of variance for combining ability in this experiment, revealed significant differences among parents, direct crosses and reciprocal crosses indicating the existence of wider variability in the material under study for all the characters. However, reciprocal crosses did not exhibit significant variation for plant height and grain zinc. The ratio of GCA/SCA variances revealed that non-additive gene action was predominant in controlling all characters studied barring grain zinc. Predictability ratio revealed that grain zinc content was found to be governed by additive gene action with little role of non-additive gene action. IS 2248 and IS 20843 were found to be promising general combiners based on *gca* effects and three hybrids *viz.,* IS 2248 X IS 20843, IS 20843 X IS 2248 and IS 2248 X PVK 801 were proven to be superior for grain zinc based on *per se* performance, significant *sca* effects and heterosis over standard check. Plant height and 100-grain weight had positive correlation with grain zinc, while days to 50 % flowering showed negative correlation with grain zinc during both the *postrainy* seasons, 2010 and 2011, indicating the possibility to enhance the grain zinc content in tall genotypes with early crop duration. Grain yield showed positive correlation in 2010, while negative correlation in 2011 with grain zinc. This difference in association of grain yield with grain zinc can be attributed to the influence of environment on these traits. Partitioning of correlation coefficients of grain yield and other important traits with grain zinc content into direct and indirect effects revealed that plant height showed positive direct effect, while days to 50 % flowering and grain yield showed negative direct effect on grain zinc consistently in both the seasons. Grain yield showed negative direct effect on grain zinc content consistently in both the seasons. Many of the characters had positive indirect effects through plant height, while negative direct effects through grain yield on grain zinc. Direct selection of plant height might be rewarding for enhancement of grain zinc content since it revealed true relationship with grain zinc content. Higher magnitude of residual effect in both the seasons indicated that it might be necessary to include some more characters closely related with grain zinc.

Conclusions and Future Strategy:

IS 13211 and IS 2263 were found to be promising parents with high *gca* effects for grain iron and SPV 1359 X IS 13211, IS 10305 X IS 13211 and IS 10305 X IS 2263 were found to be promising hybrids with high *sca* effects for grain iron in the first experiment. Grain iron was found to be governed by additive gene action suggesting that this trait could be improved by hybridization followed by simple selection through pedigree method of breeding.

IS 2248 and IS 20843 were found to be promising parents with high *gca* effects for grain zinc and IS 2248 X IS 20843, IS 20843 X IS 2248 and IS 2248 X PVK 801 were found to be promising hybrids for grain zinc with the desirable *sca* effects, heterosis and *per se* performance in the second experiment. Grain zinc was found to be governed by additive gene action with little role of non-additive gene action indicating that this trait could be improved by hybridization followed by simple selection through pedigree method of breeding.

There would be little opportunity for exploitation of heterosis for improving grain iron in first experiment and grain zinc in second experiment, considering the preponderance of additive gene action in conditioning these two traits in two separate experiments, though heterosis for grain yield and other traits is widely exploited in sorghum. Both female and male parents need to be improved for iron and zinc contents for enhancing these micronutrients in the hybrids. The knowledge and material generated in the investigation could be utilized in future sorghum breeding programmes.

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The pattern of “Literature cited” presented above is in accordance with the guidelines for the Thesis presentation for Acharya N.G. Ranga Agricultural University, Hyderabad.

* Originals not seen