Intra- specific variation in response of *Jatropha* (*Jatropha curcas* L.) to elevated CO₂ conditions

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Published online: 3 April 2012

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Abstract Twenty genotypes of *Jatropha* collected from diverse eco-geographic regions from the states of Chhattisgarh (3), Andhra Pradesh (12), Rajasthan (4) and Uttarakhand (1) of India were subjected to elevated CO₂ conditions. All the genotypes showed significant difference ($p < 0.05$ and 0.01) in the phenotypic traits in both the environments (elevated and ambient) and genotype $\times$ environment interaction. Among the physiological traits recorded, maximum photosynthetic rate was observed in IC565048 ($48.8 \mu\text{mol m}^{-2} \text{s}^{-1}$) under ambient controlled conditions while under elevated conditions maximum photosynthetic rate was observed in IC544678 ($41.3 \mu\text{mol m}^{-2} \text{s}^{-1}$), and there was no significant difference in the genotype $\times$ environment interaction. Stomatal conductance (Gs) emerged as the key factor as it recorded significant difference among the genotypes, between the environments and also genotype $\times$ environment interaction. The Gs and transpiration (E) recorded a significant decline in the

genotypes under the elevated CO₂ condition over the ambient control. Under elevated CO₂ conditions, the minimum values recorded for Gs and E were $0.03 \text{ mmol m}^{-2} \text{s}^{-1}$ and $0.59 \text{ mmol m}^{-2} \text{s}^{-1}$ respectively in accession IC565039, while the maximum values for Gs and E were $1.8 \text{ mmol m}^{-2} \text{s}^{-1}$ and $11.5 \text{ mmol m}^{-2} \text{s}^{-1}$ as recorded in accession IC544678. The study resulted in the identification of potential climate ready genotypes viz. IC471314, IC544654, IC541634, IC544313, and IC471333 for future use.

Keywords Elevated CO₂ · Genotypes · Phenotypic traits · Physiological traits · Adaptation · *Jatropha curcas*

Introduction

The impact of climate variation/climate change has been realized on the global agriculture through its impact on yields, as lower rates of increase in yields in areas of Europe with more extreme conditions have been reported (Schar et al. 2004). Significant variation in the climate is attributed to increased levels of greenhouse gases viz. CO₂, CH₄, NO₂, CFCs as a fallout of enhanced human activities like increased burning of fossil fuels, increased use of CFCs, and increased agricultural activities. Atmospheric CO₂ concentration are estimated to range between 540 and $970 \mu\text{mol mol}^{-1}$ by 2100. Plants responses to rising CO₂ vary, involving complex responses of underlying growth and development, which will affect the plant and vegetation growth as demonstrated by numerous experiments and simulation studies. Changing atmospheric CO₂ may reflect on adaptive responses to altered plant carbon and water relations (Robinson 1994). For example, short term exposure of C₃ plants to elevated CO₂ was reported to stimulate photosynthesis (Eamus and Jarvis 1989; Gilford 1992), producing major

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gains in biomass as a result of the improved competitiveness of carbon dioxide over oxygen as a substrate for the photosynthetic enzyme, ribulose-1,5-bisphosphate carboxylase-oxygenase (Rubisco) (Bowes 1993) or it may lead to decline in stomatal density, as was reported in case of *Olea europaea*, where 40 % decline was reported over a period of 3,000 year indicating linear and negative response to increasing atmospheric CO₂ concentration (Beerling and Chaloner 1993). However, the short term CO₂ enrichment or depletion results have indicated that CO₂ may alter the pattern of stomatal and epidermal cell development, although the direction and magnitude of these effects vary considerably among species (Malone et al. 1993). Adaptive response of plants grown under elevated CO₂ can be positive, negative or indeed negligible (Ceulemans and Mousseau 1994). Most of the research concern was on differential species response (Hunt et al. 1991; Poorter 1993) and less attention has been paid to intra-specific or intra-population responses, although variation in response to CO₂ at these levels could affect predictions of the ecological and evolutionary consequences of global change for communities and ecosystems as observed by Bazzaz (1990); Geber and Dawson (1992). Genotype-specific CO₂ responses of fitness related traits could favour selection of a new set of genotypes in a higher CO₂ environment, altering the course of natural selection within populations (Curtis et al. 1996). *Jatropha curcas* L. is a potential bioenergy crop known for its sturdy nature and potential to adapt to wide environmental conditions. Hence, a study to understand the variation in genotype-specific/intra-specific response in *Jatropha* to elevated CO₂ conditions was undertaken with an objective to identify ‘climate ready’ genotypes, if any. Since *Jatropha* is a perennial plant species taken up in mass plantation, identification of such genotypes assumes immense significance.

Materials and methods

Twenty genotypes of *Jatropha* collected from diverse agro-ecological zones were evaluated for their response to future increase in CO₂ conditions (700 ppm) under Open Top Chamber (OTC) setup in open field conditions. Seedlings of these 20 genotypes were raised in nursery bags, with potting mixture comprising of sand, red soil and Farm Yard Manure (FYM) in the ratio of 1: 1: 1. The nursery bags with one seedling per bag were shifted to OTCs, 1 week after germination.

Open top chamber (OTC)

The two OTCs comprised of ambient (380 ppm) and elevated CO₂ (700 ppm) conditions. OTCs are 3×3×3 m square type structures, the sides of the OTCs are covered with 120 µ thick polyvinyl chloride (PVC) sheet to have

more than 90 % transmittance of the light and the chambers are open from the top. The response of these genotypes to elevated CO₂ level (700±50 ppm) on plant growth was recorded after 60 days of exposure. Plants were maintained stress-free by regular irrigation. Each chamber contained three replicates of each of the 20 genotypes. The elevated level of CO₂ in OTC was maintained at 700±50 ppm at crop canopy level by continuously injecting 100 % CO₂ into plenum, where it was mixed with ambient air from air compressor before entering into the chamber. Other OTC was maintained at ambient CO₂ level (380 ppm) without any external CO₂ supply and served as an ambient control chamber. The air sample from each chamber was drawn at 3 min interval into non-dispersive infrared (NDIR) CO₂ analyzer (California Analytical) and the set CO₂ concentration was maintained with the help of solenoid valves, rotameters, PCs, Program Logic Control (PLC) and Supervisory Control and Data Acquisition (SCADA) software. Throughout the experimental period, continuous measurements of relative humidity and temperature of the OTCs were possible with the sensors fitted inside the chambers. The observations on phenotypic traits viz., the leaf number, leaf area, plant height, girth of the plant, pedicel length, root length, root volume, stem, leaf and root dry weight were recorded on individual plants after 60 days of exposure. The root length was recorded on main root of each plant and root volume was measured by displacement of water and expressed as ml/pl. The leaf area was measured with leaf area meter (LI-3100) and expressed as cm² per plant. The dry weight of shoot, root and leaf were recorded separately after thorough drying of plant material in hot air oven at 65 °C.

Data recording

Observations on the physiological traits viz., net photosynthetic rate (P_n, µmol CO₂ m⁻² sec⁻¹), transpiration rate (E, mmol H₂O m⁻² sec⁻¹), stomatal conductance (G_s, mmol m⁻² sec⁻¹) and intercellular CO₂ content (C_i, µmol mol⁻¹) were recorded using the portable photosynthetic system (model LICOR-6400). A CO₂ cartridge was used in portable photosynthesis system (LICOR 6400) in order to get stable CO₂ concentrations and to maintain CO₂ concentration of the growth conditions into the leaf chamber. The block temperature of the system was set at ambient temperature and light at 1,000 µmol m⁻² s⁻¹. The data were statistically analysed to test the significance of treatment and their interactions by MSTAT C.

Results and discussion

The response of *Jatropha curcas* genotypes to the elevated CO₂ levels for phenotypic and physiological traits was studied and results are furnished below.

Variation in response for phenotypic traits

The ANOVA of the phenotypic traits has been presented in Table 1. The seedlings after 60-day exposure to elevated CO₂ in replicated experiment with ambient (380 ppm) and elevated CO₂ (700 ppm) in OTCs showed significant difference ($p < 0.05$ and 0.01) among all the traits *viz.*, plant height, girth, petiole length, leaf number, leaf area, leaf dry weight, shoot dry weight, root length, root volume, root dry weight, total biomass, shoot: root ratio with respect to the genotypes, environments and genotypes x environment interaction were recorded. The mean values of all phenotypic traits under ambient control and elevated CO₂ condition are presented in Table 2. All the genotypes recorded an increase in plant height under the elevated CO₂ conditions. The percentage increase under elevated CO₂ over ambient control ranged from 1.2 (IC471314) to 58 % (IC544685). The maximum percentage increase in girth was recorded by IC544685 (31 %) and the girth remained unchanged under elevated CO₂ conditions in four genotypes *viz.*, IC537863, IC541634, IC544678 and IC471318. An interesting observation recorded for petiole length was that all the genotypes showed incremental response to petiole length under elevated CO₂ conditions over ambient control except, IC541634, which recorded identical values under both conditions. Accession, IC544693 recorded maximum percentage increase (110 %) in petiole length. Leaf number improved under elevated conditions in all the genotypes. IC541688 recorded the maximum percentage increase (45 %) and IC537938 recorded identical values (10) under both the environments. The response to leaf area was more prominent among all the traits recorded across all the genotypes. The percentage increase recorded under elevated CO₂ conditions ranged from 22 % (IC537916) to 122 % in IC565039 (Fig. 1). There was increase in leaf dry weight in line with increase in leaf area. However, the maximum increase in leaf dry

weight under elevated CO₂ conditions over the ambient control was recorded in IC565039 (126 %); whereas genotypes IC544660 and IC471333 recorded minimum (14 %) increase. The root length also responded positively at elevated CO₂ in all the genotypes except, IC471313 which recorded a drop of 13 % over the ambient control. The percentage increase ranged from 1.4 % (IC538055 and IC471314) to 20 % (IC544678). Genotypes IC565044 and IC541651 recorded maximum increase (88 %) in root volume under the elevated CO₂ conditions (Fig. 2). Shoot dry weight, along with leaf area, was most conspicuous in its response to elevated CO₂ (Fig. 3). All the genotypes, except IC471333, recorded increase in shoot dry weight. The percentage increase over ambient control ranged from 1 % in IC471314 to 206 % in IC544685 (Fig. 3). The response of root dry weight was not commensurate with the increase in shoot dry weight. Accession IC565044 (74 %) recorded maximum percentage increase under the elevated CO₂ over ambient control, whereas accession IC5446016 recorded no variation in root dry weight under ambient and elevated conditions. All genotypes recorded increase in total biomass under elevated CO₂. The maximum increase in total biomass under elevated CO₂ over ambient/control was recorded in IC544685 (125 %) and minimum increase was recorded in IC4713131 (6 %). Shoot : root ratio ranged from 2.8 to 4.5 (IC541688) under elevated CO₂ conditions whereas it extended from 1.8 (IC565039) to 5.8 (IC471314) under ambient control. The maximum increase in the ratio was recorded in IC565039 (106 %). Five genotypes *viz.*, IC541634 (−14 %), IC544654 (−18 %), IC471313 (−7.9 %), IC471314 (−31 %) and IC471333 (−5.6 %) recorded decline in the ratio where the response of root was higher than shoot.

Majority of the selected genotypes recorded an enhancement in all the phenotypic traits when they were exposed to elevated CO₂. Similar results were also reported in tomato

Table 1 ANOVA for various phenotypic traits at 60 DAE for *Jatropha* genotypes under ambient (380 ppm) and elevated CO₂ (700 ppm) environments in OTCs

Source	DF	Mean sum of squares											
		Plant height (cm)	Leaf number (No.)	Petiole length (cm)	Girth (cm)	Root length (cm)	Root volume (ml)	Leaf area (cm ²)	Leaf dry weight (g)	Shoot dry weight (g)	Root dry weight (g)	Total biomass (g)	Shoot/Root ratio
Replications	2	38.0	0.3	1.2	0.1	39.8	2.8	404.6	0.2	0.0	0.0	0.2	0.0
Genotypes	19	68.0 ^a	5.1 ^a	18.4 ^a	0.2 ^b	27.9 ^b	22.4 ^a	62,072.4 ^a	2.3 ^a	29.6 ^a	6.0 ^a	62.4 ^a	1.6 ^a
Environment	1	546.1 ^a	7.6 ^b	213.0 ^a	0.6 ^a	7.85	120.0 ^a	734,232.3 ^b	111.0 ^a	773.0 ^a	40.6 ^a	1,998.3 ^a	9.8 ^a
Genotypes x Environment	19	45.2 ^a	3.7 ^a	7.5	0.0	9.3	9.06 ^a	44,398.0 ^a	2.5 ^a	23.0 ^a	2.5 ^a	46.7 ^a	1.6 ^a
Error	78	18.3	1.3	8.2 ^a	0.1	14.9	1.7	2,668.0	0.1	0.1	0.1	0.2	0.0

^a Significance at 1 %

^b at 5 % level

DAE Days after exposure, DF Degrees of freedom

Table 2 Mean values of various phenotypic traits at 60 DAE for genotypes under ambient (380 ppm) and elevated CO₂ (700 ppm) environments in OTCs (cont)

Character	Local		IC565048		IC537863		IC538055		IC537916		IC565039		IC544660		IC471333		IC541634		IC565044	
	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
Plant height (cm)	32.6	34.0	28.3	33.6	27.16	32.6	27.8	30.8	29.0	36.3	30.5	37.8	27.67	35.5	27.3	31.0	27	29.8	20.0	25.3
Leaf Number	8.6	9.5	9.0	10.6	9.0	10.3	9.0	10.6	9.3	10.6	10.3	12.0	9.3	10.3	9.0	10.6	10.0	10.6	8.3	10.3
Petiole length (cm)	9.6	10.0	10.0	16.1	9.3	11.0	8.0	13.8	9.7	12.5	9.3	10.4	10.0	11.4	10.6	10.8	10.5	10.5	7.0	8.1
Girth (cm)	1.0	1.2	1.3	1.5	1.4	1.4	1.5	1.6	1.4	1.7	1.5	1.6	1.3	1.4	1.1	1.2	1.3	1.3	1.3	1.6
Root length (cm)	22.6	26.0	24.6	27.3	24.0	25.5	22.0	22.3	23.6	26.0	24.0	24.6	23.0	24.6	23.0	24.0	21.3	24.6	19.8	23.3
Root volume (ml)	9.0	10.0	10.0	11.7	10.0	11.6	11.6	13.3	11.6	15.0	11.6	13.3	7.6	8.3	7.4	9.0	9.0	12.3	8.3	15.6
Leaf area (cm ²)	232.5	426.0	369.1	465	289.3	549.0	276.4	466.0	253.4	309.3	300.0	667.3	481.0	606.3	300.0	428.3	405	666.3	261	460.6
Leaf dry weight (g)	3.0	4.2	3.6	5.2	3.7	6.3	4.1	5.2	3.0	6.4	3.1	6.9	5.1	5.8	3.5	4.0	4.7	7.1	2.7	6.1
Shoot dry weight (g)	9.6	13.6	10.2	12.9	10.4	16.1	13.4	15.2	11.9	19.1	6.3	18.3	9.5	13.5	10.2	10.8	10.8	13.9	9.8	18.8
Root dry weight (g)	5.4	5.5	5.2	6.4	4.9	6.3	6.2	7.2	6.0	7.6	5.2	6.8	4.8	4.8	3.8	4.4	4.4	7.0	5.1	8.9
Total biomass (g)	18.0	23.3	19.0	24.5	19.0	28.7	23.7	27.6	20.9	33.1	14.6	32.0	19.4	24.1	17.5	19.2	19.9	28.0	17.6	33.8
Shoot/Root ratio	2.3	3.2	2.7	2.8	2.9	3.6	2.8	2.8	2.5	3.4	1.8	3.7	3.0	4.0	3.6	3.4	3.5	3.0	2.5	2.8

Character	IC541651		IC541664		IC544678		IC471313		IC537938		IC544685		IC544654		IC541688		IC471318		IC471314	
	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
Plant height (cm)	24.0	36.1	25.3	31.8	22.6	30.0	25.6	27.3	23.5	32.0	23.8	37.6	26.5	31.6	32.0	40.6	20.6	25.0	32.6	33.0
Leaf Number	8.6	9.6	8.3	10.0	9.0	11.0	7.6	8.6	10.0	10.0	9.0	9.6	9.3	10.6	8.3	12.0	6.3	7.0	7.3	9.0
Petiole length (cm)	8.9	13.3	6.1	12.8	12.8	14.6	9.6	13.6	8.6	12.0	9.3	10.3	10.8	13.3	8.3	10.6	12.5	17.6	11.3	15.6
Girth (cm)	1.3	1.6	1.4	1.6	1.0	1.0	1.3	1.5	1.2	1.4	1.3	1.7	1.3	1.5	1.4	1.5	1.0	1.0	1.2	1.5
Root length (cm)	20.0	22.6	23.0	25.1	26.3	31.5	24.0	27.0	26.3	29.0	23.6	25.3	21.5	23.5	22.0	24.6	20.8	21.5	20.0	20.3
Root volume (ml)	6.6	12.4	9.0	12.3	5.0	8.3	6.2	6.6	9.0	9.4	7.3	11.4	8.3	11.6	9.0	9.1	5.0	9.2	9.0	10.3
Leaf area (cm ²)	282.7	468.3	335.6	652.3	372.6	518.4	352.0	471.6	318.5	609.0	320.0	640.0	406.9	608.6	377.4	602.6	402.1	560.6	447.2	609.6
Leaf dry weight (g)	3.2	5.7	4.0	7.0	3.6	4.7	4.5	6.3	3.1	6.2	3.6	6.2	4.1	5.4	4.5	7.0	3.3	5.1	3.7	5.4
Shoot dry weight (g)	10.0	18.8	11.5	19.8	5.9	8.7	11.0	12.7	7.2	13.6	6.8	20.8	11.9	12.5	9.9	14.5	6.4	11.9	16	16.1
Root dry weight (g)	4.0	6.7	5.6	7.4	2.5	3.4	4.1	5.5	4.2	5.5	4.4	6.3	4.7	6.5	4.7	4.8	4.0	5.2	3.4	5.4
Total biomass (g)	17.2	31.2	21.1	34.2	12.0	16.8	19.6	24.5	14.5	25.3	14.8	33.3	20.7	24.4	19.1	26.3	13.7	22.2	23.1	26.9
Shoot/Root ratio	3.3	3.7	2.8	3.6	3.8	3.9	3.8	3.5	2.5	3.6	2.4	4.3	3.4	2.8	3.1	4.5	2.4	3.3	5.8	4.0

DAE Days after exposure

Fig. 1 Percent increase in leaf area under the elevated CO₂ condition over ambient control

under elevated CO₂ by (Li et al. 2007). They reported that plant height, stem thickness, total dry weight, dry weight of the leaves, stems and roots, G value (total plant dry weight/seedling days), chlorophyll content, photosynthetic rate increased with elevated CO₂. The percentage increase in plant height under elevated CO₂ over ambient control was 58 % (IC544685). Bhattacharya et al. (1985) reported significant increase in plant height in sweet potato and cowpea under elevated CO₂. Among the traits studied, leaf area is the most responsive trait and more than 10 genotypes out of 20 recorded an increase of more than 50 % with a maximum of 122 %. The same trend was found with leaf dry weight; as in majority of the genotypes increment in leaf area was coupled with increased leaf dry weight. In Local accession (CRIDA-1), the response of leaf area is more than the increments in leaf dry weight, hence reduced specific leaf weight.

Fig. 2 Percent increase in root volume under the elevated CO₂ condition over ambient control

Fig. 3 Percent increase in shoot dry weight under the elevated CO₂ condition over ambient control

Several studies showed that the extra C in plant leaves induced by elevated CO₂ resulted in increase in leaf size, number of branches or tillers and numbers of nodes along the branches which support leaves, and hence leaf area. A reverse trend for this was recorded with IC537916, which resulted a thicker leaves under elevated CO₂ conditions i.e., increase in specific leaf weight. Huber et al. (1984) concluded that the increase in specific leaf mass was mostly due to the increase in starch content and/or increase in palisade cells. The highest responsiveness to shoot dry weight in IC544685 is due to its maximum responsiveness for both plant height and girth under elevated CO₂ and in this particular genotype this trait contributed for its high responsiveness to total biomass also. Among the root traits, the increment in root dry weight or responsiveness to root dry weight to elevated CO₂ was contributed by increment in root volume rather than root length. This clearly indicated that elevated CO₂ is promoting more fine roots/branching and root hairs formation. Similarly, Baker et al. (1990) recorded around 65 % more actively growing roots in rice at 800 ppm, whereas the elongation rate of individual root axes was not affected.

It is also interesting to observe that in different genotypes the extent of responsiveness for leaf, stem and root are significantly varied. The genotypes with a negative increment in shoot: root ratio implies for its better responsive to root traits. Such genotypes viz., IC471314, IC544654, IC541634, IC544313, and IC471333 may be suitable for future high CO₂ and moisture limiting conditions. Among these five genotypes, IC541634 also responded significantly for leaf area and leaf dry weight along with the root dry weight and total biomass. Stulen and den Hertog (1993) made a review of the dry matter partitioning in response to elevated CO₂ and concluded that there is a wide variability

Table 3 ANOVA for various physiological traits at 60 DAE for genotypes under ambient Control (380 ppm) and elevated CO₂ (700 ppm) environments

Source	DF	Photosynthetic rate ($\mu\text{mol m}^{-2}\text{ s}^{-1}$)	Stomatal conductance ($\text{mmol m}^{-2}\text{ s}^{-1}$)	Transpiration rate ($\text{mmol m}^{-2}\text{ s}^{-1}$)	Temperature difference (°C)
Replications	2	2.0	2.1	44.0	1.1
Genotypes	19	31.6	1.4 ^b	22.3	0.7 ^a
Environment	1	329.3 ^a	14.5 ^b	894.0 ^b	12.2 ^a
Genotypes x Environment	19	20.5	0.9 ^b	20.2	0.6
Error	78	25.2	0.8	19.0	0.4

^aSignificance at 1 % level^bat 5 % level

DAE Days after exposure, DF Degrees of freedom

in root: shoot ratio and their observations varied from negative, no change and positive.

The plant traits like plant height, girth and petiole length make possible for increase in yield by increase in photosynthetic area, translocation efficiency and entrapment of photosynthetic active radiation respectively. The increase in leaf number, leaf area, leaf dry weight which primarily constitutes an increase in photosynthetic area is wanted. Leaf area development is an important component that determines total plant productivity (Monteith 1977). However, it has been noticed in *Jatropha* that source is not the limitation. Enhanced leaf area due to elevated CO₂ has also been reported by Taylor et al. (1994a, b) and Gardner et al. (1995). The proliferation of leaf number and leaf area may result in mutual shading and leading to decreased photosynthetic efficiency ultimately leading to decrease in yield. Unless the architecture of the plant along with the increased petiole length orients the leaves in a manner leading to maximum efficiency, as was evident in the present study with increase in petiole length in almost all the genotypes. Shoot dry weight chiefly contributes to increased photosynthates which are highly appropriate for translocating the same to the economic parts- the seeds. The root which is principally involved in the absorption of moisture and nutrients plays an important role in this hardy species in the moisture stress environments. Hence, genotypes which register proliferation in root length, root volume and dry weight under elevated CO₂ have an edge over other genotypes in enduring the future stress environments. In the present study, IC565044, which recorded in high percentage increase in root length (18 %), root volume (88 %), leaf dry weight (126 %) and root dry weight (74 %), and accession IC541651, which registered high increase for plant traits like plant height (50 %), root volume (88 %) and root dry weight (67 %) and IC544685 which enlisted high percentage increase in traits like plant height (58 %), girth (31 %), leaf area (100 %), shoot dry weight (206 %) and total biomass (125 %) may be appropriate for changed climatic conditions with high levels of CO₂. Similar results in increase in total dry weight, stem, root and leaf dry weight; root and shoot length, leaf area and root: shoot ratio were reported by Vanaja et al. (2006) in four crops belonging to three crop groups viz., cereals, pulses and

oilseeds. They found maximum increase of total dry weight (79.7 %), stem dry weight (100.95 %), root dry weight (78.18 %) and leaf dry weight (71.18 %), shoot length (7.37 %) and leaf area (52.54 %) in black gram followed by sunflower, groundnut and sorghum. Kimball et al. (2002) reviewed that C₄ crops in general respond less, compared to C₃ crops under elevated CO₂ and *Jatropha* being a C₃ crop responded well under elevated CO₂. Vanaja et al. (2008) studied growth and yield responses of castor bean (*Ricinus communis* L.) which belongs to the same family as *Jatropha*, at two elevated CO₂ levels (550 ppm and 700 ppm) in open top chambers (OTCs). They reported that the growth characteristics – root and shoot lengths, root volume, root: shoot ratios, leaf area, dry weights of different plant parts, leaf area duration and crop growth rate increased significantly with 550 ppm and 700 ppm of CO₂ levels. Kim et al. (2011), in a pot experiment studied the effects of elevated CO₂ concentration on accumulation and intra-plant partitioning of dry matter (DM). Overall, total grain DM increased with elevated CO₂ by 69.6 % and shoot DM increased 46.6 % in rice.

Variation in response for physiological traits

The two-way ANOVA revealed that there was significant difference between the genotypes for stomatal conductance, transpiration rate and temperature difference. Between the two environments significant difference was observed for photosynthetic rate, stomatal conductance, transpiration rate and temperature difference and in the accession x environment interaction, significant difference was observed only in stomatal conductance (Table 3). The mean values for the above traits are presented in Table 4. The maximum photosynthetic rate was observed in IC565048 ($48.8 \mu\text{mol m}^{-2}\text{ s}^{-1}$) under ambient controlled conditions and the maximum recorded under elevated CO₂ conditions was $41.3 \mu\text{mol m}^{-2}\text{ s}^{-1}$ in IC544678 (Table 4). However, there was no significant difference in the accession x environment interaction. Stomatal conductance emerged as the key factor as it recorded significant difference among the genotypes, environments and also genotype × environment interaction. The

Table 4 Mean values of physiological traits at 60 DAE for genotypes under ambient control (380 ppm) elevated CO₂ (700 ppm) environments

Character	ICS65048		ICS37863		ICS38055		ICS37916		ICS65039		ICS44660		IC471333		ICS41634		ICS65044	
	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
Photosynthetic rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	38.4	39.3	48.8	37.0	46.2	36.1	42.2	38.4	42.3	39.2	39.2	38.7	44.9	39.8	39.2	39.3	44.5	39.4
Stomatal conductance ($\text{mmol m}^{-2} \text{s}^{-1}$)	4.3	1.2	1.3	0.9	1.3	0.4	0.9	0.4	1.5	1.2	1.2	1.5	1.2	1.5	1.1	1.2	1.0	0.6
Transpiration rate ($\text{mmol m}^{-2} \text{s}^{-1}$)	18.0	9.1	10.3	6.8	10.7	3.6	7.2	4.4	11.3	5.5	5.5	8.4	9.9	10.7	10.4	9.7	8.7	4.9
Temperature difference (°C)	0.2	0.3	0.6	0.8	0.3	1.2	0.6	1.5	0.2	1.0	0.2	0.6	0.4	0.1	0.5	0.4	1.0	1.3

Character	ICS41651		ICS41664		ICS44678		IC471313		ICS37938		ICS44685		ICS44654		ICS41688		IC471318		IC471314	
	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
Photosynthetic rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	41.6	40.0	39.4	39.2	37.2	41.3	40.0	36.3	37.6	37.3	36.8	33.1	38.9	33.3	36.8	36.3	38.8	36.2	40.8	37.8
Stomatal conductance ($\text{mmol m}^{-2} \text{s}^{-1}$)	1.4	0.7	1.0	0.6	1.5	1.8	1.7	0.2	1.5	0.6	1.3	0.2	1.5	0.14	1.5	0.45	1.0	0.52	0.86	0.67
Transpiration rate ($\text{mmol m}^{-2} \text{s}^{-1}$)	12.0	7.0	8.5	5.6	10.7	11.5	11.7	2.3	10.9	5.1	10.1	2.5	13.9	1.9	13.5	3.4	11.4	4.7	9.9	4.5
Temperature difference (°C)	0.3	0.8	0.7	1.2	0.0	0.2	0.0	1.5	0	1.5	0.3	2.0	0.5	1.7	0.4	1.3	1.1	1.0	1.3	1.1

DAE Days after exposure

Fig. 4 Response of stomatal conductance ($\text{mmol m}^{-2} \text{s}^{-1}$) under the elevated CO_2 condition over ambient control

stomatal conductance recorded a significant decline in the genotypes under the elevated CO_2 condition over the ambient control (Fig. 4). The minimum value recorded under elevated conditions was $0.03 \text{ mmol m}^{-2} \text{s}^{-1}$ (IC565039) and the maximum value was $1.8 \text{ mmol m}^{-2} \text{s}^{-1}$ in IC544678 (Table 4). The maximum decline was recorded in IC565039 (−97 %) under elevated CO_2 conditions over the ambient control and the minimum decline was in IC537916 (−20 %) as depicted in Fig. 4. Transpiration rate showed no significant difference in the genotypes $\times$ environment interaction. However, significant difference was observed between the treatments and environments ($p < 0.05$). The minimum value recorded under elevated conditions was $0.59 \text{ mmol m}^{-2} \text{s}^{-1}$ (IC565039) and the maximum was $11.7 \text{ mmol m}^{-2} \text{s}^{-1}$ in IC544678. ΔT , which is air minus leaf temperature inside the photosynthesis cuvette, showed significant difference between the genotypes, environments and genotype $\times$ environment interaction. The temperature difference showed an increase under elevated CO_2 conditions. The maximum increase was in the accession IC541688.

Among the physiological traits, the maximum photosynthetic rate was observed in IC565048 ($48.8 \mu\text{mol m}^{-2} \text{sec}^{-1}$) and under elevated conditions, the maximum photosynthetic rate recorded was in the genotype IC544678 ($41.3 \mu\text{mol m}^{-2} \text{sec}^{-1}$) i.e. there is a slight decline in the photosynthetic rate. In the present study, this trend was observed in majority of the genotypes (16 out of 20), but the decrease was not significant. This may be due to photosynthetic acclimation. Fernandez et al. (1999), studied the response of four tropical deciduous species including *Jatropha gossypifolia*, and found increase in rates of net photosynthetic rates upto 3.5 times on an average in the initial stages which dampened later but maintained higher photosynthetic values than ambient control. They also recorded decrease in carboxylation

efficiency. This may be due to acclimation (Gunderson and Wullschlegel 1994). Zhang and Xu (2007) reviewed the mechanisms of photosynthetic acclimations to elevated CO_2 concentrations. They pointed that besides the possible effects of respiration enhancement and excessive photosynthate accumulation, RuBP carboxylation limitation and RuBP regeneration limitation are probably the main factors leading to the photosynthetic acclimation. Ghildiyal and Sharma-Natu (2002) also reviewed the photosynthetic acclimation, change in photosynthetic efficiency of leaves due to long term exposure to elevated CO_2 , in response to rising CO_2 . Stomatal conductance and transpiration rate declined under elevated CO_2 conditions, the maximum decline in stomatal conductance was recorded in IC565039 (−97 %) and minimum decline was in IC537916 (−20 %). Ainsworth and Rogers (2007) reviewed the response of stomatal conductance to rising CO_2 and observed that elevation of CO_2 in FACE experiments reduced stomatal conductance by 22 %. Various studies by De Souza et al. (2008) in sugarcane; (Kimball et al. 2002) in wheat (*Triticum aestivum* L.), perennial ryegrass (*Lolium perenne*), and rice (*Oryza sativa* L.) which are C_3 grasses; sorghum (*Sorghum bicolor* (L.) Möench), a C_4 grass; white clover (*Trifolium repens*), a C_3 legume; potato (*Solanum tuberosum* L.), a C_3 plant with tuber storage; and cotton (*Gossypium hirsutum* L.) and grape (*Vitis vinifera* L.) which are C_3 woody perennials showed reduced stomatal conductance and transpiration rate with elevated CO_2 .

Although there was variation in response to the genotypes, *Jatropha* as a plant species responded positively to the elevated CO_2 conditions. Among the phenotypic traits, leaf area is the most responsive along with leaf dry weight and genotypes also recorded an increment in shoot and root dry weight which helped in identification of five lines namely IC471314, IC544654, IC541634, IC544313, IC471333 suitable for high CO_2 and moisture stress conditions. Among the physiological traits, photosynthetic rate showed decline, but it was not significant. Based on our results, *Jatropha* may positively respond to elevated CO_2 , but at levels lower than 700 ppm. However, reduced stomatal conductance and transpiration rate were recorded under elevated CO_2 conditions which can be used in the identification of promising/efficient genotypes under elevated CO_2 for moisture stress conditions, as it is reported to be hardy crop having wider adaptability with great degree of phenotypic plasticity.

Acknowledgements The authors are thankful to the Director, NBPGR and Head, Plant Quarantine Division NBPGR, New Delhi and Director, CRIDA, Hyderabad for continued support and extending the necessary facilities for the present study. The financial support of RSAD, Government of Andhra Pradesh for the above study is gratefully acknowledged.

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