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Is Cassava (*Manihot esculenta Crantz*) a Climate "Smart" Crop? A Review in the Context of Bridging Future Food Demand Gap

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Abstract

Climate change and its impact on agriculture are one of the ongoing research areas, and the major task among agricultural managers is to meet the food demand in the future in the context of the production gap of major food grain crops. Literature analysis is carried out to understand the climate resilience of cassava, one of the major tuber crops and is considered to bridge the food demand gap in the near future. Systematic analysis of literature includes influence of changing environmental parameters such as temperature, solar radiation, photoperiod, air humidity, soil water deficit, salinity, elevated ozone and CO_2, combined effects of elevated CO_2 with temperature, water deficit and salinity to the growth and yield of cassava along with its resilience to biotic stresses and its climate suitability. Studies indicate cassava can tolerate a temperature level of up to 40 °C, and thereafter the rate of photosynthesis decreases. Cassava can be cultivated in regions with variations in solar radiation without much compromise in its yield in the context of global dimming of sunshine duration. The resilience to water stress and air humidity variations are adapted by reducing stomatal conductance without influencing the rate of photosynthesis. Cassava has also an inbuilt mechanism to cope with water scarcity by leaf drooping. Already established cassava can tolerate a salinity level of up to 150 mM and the younger ones can tolerate up to a level of 40 mM. Studies also indicate a strong positive influence of elevated CO_2 of up to 700 ppm on the rate of photosynthesis and yield of cassava. Elevated CO_2 enhances the resilience of cassava to water stress and salinity. Similarly, the combined effect of elevated CO_2 and higher temperatures also increases the yield attributes of cassava. These all indicate the resilience of cassava to the changing climate and it ensures as an insurance crop as well as food security crop in the near future. Studies show its resilience to biotic stresses as well. Climate suitability studies also show its suitability in the present locations in the near future as well as its adaptation to other areas. However, the research gap is identified in areas of influence of elevated ozone on growth characteristics of cassava. This study also recommends identifying the extent of tolerance level of cassava to the influence of the combined effect of salinity and elevated CO_2. Further, researchers need to concentrate on developing biotic as well as abiotic stress-tolerant genes in cassava varieties to increase its production irrespective of the changing climatic conditions.

Keywords Climate change · Resilience · Photosynthesis · Water stress · Salinity · Stress tolerance · Biotic and abiotic stresses

Introduction

Climate change and its impact on agriculture are one of the ongoing research areas worldwide. Studies already indicated the necessity of adaptation measures in agriculture in the context of climate change (Lobell et al. 2008; Malanson et al. 2014). Based on IPCC (2013), the temperature, concentrations of CO_2, and ozone (O_3) will continue to increase and the increase in temperature will be 2.6 to 4.8 °C under elevated CO_2 produced due to global warming by 2100. The increase in temperature, CO_2, and O_3 affect crop growth parameters, and hence there will be a reduction in food grain production and nutritive values of major food crops (Jarvis et al. 2012; El-Sharkawy 2014; Thornton et al. 2014; Mikkelsen et al. 2015). The expected population of 9 billion by 2050 demands an increase of 60–110% more agricultural production (Ray et al. 2013; Bedoussac et al. 2015; De Souza et al. 2017). The likely gap in demand-supply can be bridged by tuber crops, especially cassava (*Manihot esculenta* Crantz) which

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is a concentrated source of carbohydrate (Sabitha et al. 2016; Tironi et al. 2017; Manners and van Etten 2018).

Cassava (*Manihot esculenta* Crantz) is originated from Mexico and Central America (Olsen and Schaal 1999; Allem 2002). This crop is widely cultivated by small farmers in the marginal lands of Africa, Asia, and Latin America, and now it is emerging as a commercial crop in many developing countries. Figure 1 shows that Nigeria is the highest producer of cassava in the world followed by the Democratic Republic of Congo and Thailand (FAOSTAT 2017). Cassava can be cultivated in a wider range of climatic conditions as well as soils in regions from Tropic of Cancer and Tropic of Capricorn (Byju and Suja 2020). The range of temperature required for sprouting are observed as 12–17, 28–30, and 36–40 °C respectively for minimum, optimum, and maximum temperatures. Cassava can survive in areas with high variability in rainfall of 500 to 5000 mm (Allem 2002). Rather than its adaptability to poor soil conditions, a wider range of meteorological conditions, and minimum field management conditions, this crop has diverse utilization in food (Table 1), feed as well as fuel industry, and this makes cassava farmer-friendly in terms of economy. More about the cassava's physiological and climatic conditions, please refer to Byju and Suja (2020).

Cassava is an important source of carbohydrate after rice, sugarcane, and maize and is a staple food for 800 m people in the tropics and sub-tropics (McCallum et al. 2017; Putpeerawit et al. 2017). Cassava ranks first position in terms of energy production followed by maize and sweet potato (de Vries et al. 1967). Studies indicate that 70% of cassava production is utilized for human consumption, and the remaining 30% is used in the industry such as in adhesives, textiles and paper in the form of starch, glucose, and alcohol (Nguyen et al. 2007; Xie et al. 2017). The global area of cassava cultivation increased from 13.6 to 19.6 mha, and the production enhanced from 124 to 252 mt and it came to the fifth position in terms of production along with other major food crops such as maize, rice, wheat, and potato (FAO 2013). Figure 2 illustrates the percentage increase in global production of major crops and cassava from 1980 to 2015, and among them, the increase in cassava production reached near to that of Maize, one of the major foods grain crops. Studies indicate cassava cultivation has the least impact on environmental parameters compared to the other major food crops such as rice, maize, and sorghum (Reynolds et al. 2015). All these indicate the wider adaptability of cassava to cope with the food demand for the future due to the impact of climate change. This study reviews more about the resilience of cassava with the changing climate. A detailed literature analysis is carried out from the available 136 published articles to understand the influence of climate variability on growth and yield characteristics of cassava.

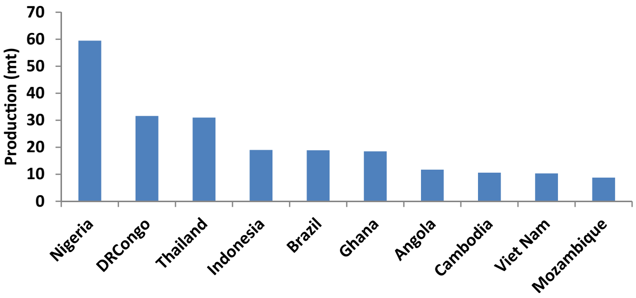

Fig. 1 Top 10 cassava producing countries and their production

Table 1 Nutritional values of cassava

Parameters	Raw cassava	Cassava roots	Cassava leaves
Food energy (kcal)	160	110–149	91
Moisture (g)	59.68	45.9–85.3	64.8–88.6
Dry weight (g)	40.32	29.8–39.3	19–28.3
Protein (g)	1.36	0.3–3.5	1.0-10.0
Lipid (g)	0.28	0.03–0.5	0.2–2.9
Carbohydrate (g)	38.06	25.3–35.7	7–18.3
Dietry fiber (g)	1.8	0.1–3.7	0.5–10
Ash (g)	0.62	0.4–1.7	0.7–4.5
Vitamins			
Thiamin (mg)	0.087	0.03–0.28	0.06–0.31
Riboflavin (mg)	0.048	0.03–0.06	0.21–0.74
Niacin (mg)	0.854	0.6–1.09	1.3–2.8
Ascorbic acid (mg)	20.6	14.9–50	60–370
Vitamin A (MICRO G)		5.0–35.0	8300–11,800
Minerals			
Ca (mg)	16	19–176	34–708
P (mg)	27	6–152	27–211
Fe (mg)	0.27	0.3–14	0.4–8.3
K (%)		0.25(0.72)	0.35(1.23)
Mg (%)		0.03(0.08)	0.12(0.42)
Cu (ppm)		2(6)	3(12)
Zn (ppm)		14(41)	71(249)
Na (ppm)		76(213)	51(177)
Mn (ppm)		3(10)	72(252)

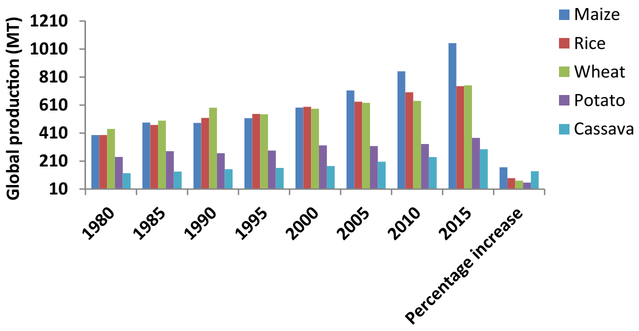

Fig. 2 Percentage increase in cultivation of major food crops from 1980 to 2015 (Source: FAOSTAT)

Climate Change and Cassava

Cassava can be cultivated in areas with limited rainfall, high temperature, low fertility soils (El-Sharkawy et al. 1993; Ceballos et al. 2011) and hence it is considered as a food security crop or insurance crop for smallholder farmers (Lebot 2009; Polthanee 2018). However, climate variability can influence the growth and yield of cassava. The environmental parameters that change with changing climate are temperature, solar radiation, rainfall, concentrations of CO_2 and ozone, and soil salinity. Therefore, the following sections discuss the impact/influence of each environmental parameter (abiotic stresses) on growth and yield of cassava followed by the resilience of cassava to biotic stresses and its climate suitability.

Abiotic Stresses

Temperature

Recent studies indicate there is a trend in the increase in maximum (Tmax) and minimum temperatures (Tmin) due to global warming (Choi et al. 2018; Herold et al. 2018). Tmax and Tmin are the two most important parameters determining the crop's physiological changes and hence the final yield. Cassava can be cultivated in wider climatic conditions (Irikura et al. 1979), even though; the variations in temperature can affect the growth and yield parameters of cassava. Based on the climate projections, studies indicate an increase in temperature reduces crop production by increasing the respiration (Asante and Amuakwa-Mensah 2015; Boansi 2017). However, the projections of temperature changes positively influence the growth and yield of cassava in the presence of elevated CO_2 (Gabriel et al. 2014). The optimum temperature for cassava is observed as 28 °C and a temperature range of 25 to 29 °C is favorable for its growth (Irikura et al. 1979; Keating and Evenson 1979). Ravi et al. (2008) reported that cassava yield is increased from 29.3 to 36.8 t ha^{-1} with the increase in mean annual temperature from 27.7 to 28.9 °C in one of the major cassava producing states in India. Cassava can tolerate a temperature range of 16 to 38 °C (Cock 1984) due to the presence of heat stress genes (Sakurai et al. 2007) compared to the other major food crops. According to Ravi et al. (2008), cassava can tolerate higher temperatures up to 40 °C, after that the photosynthetic rate will decline, and at 50 °C the rate is observed as zero (El-Sharkawy et al. 1984b). Lower temperature increases the leaf life (Irikura et al. 1979) and higher temperature (>30 °C) affects flowering as well as the life span of the leaves (El-Sharkawy 2004; Ravi and Ravindran 2006). The variations in the rate of photosynthesis with temperature are presented in Fig. 3. The increasing rate of photosynthesis is observed as 1.4 μmoles CO_2 m^{-2} s^{-1} for 1 °C rise in temperature in the range of 21.5 to 26.5 °C, and the increasing rate is 0.2 to 0.6 for 1 °C rise in temperature in the range of 25 to 35 °C (Ravi et al. 2008). The temperature requirement of cassava for its optimum growth and yield parameters are listed in Table 2.

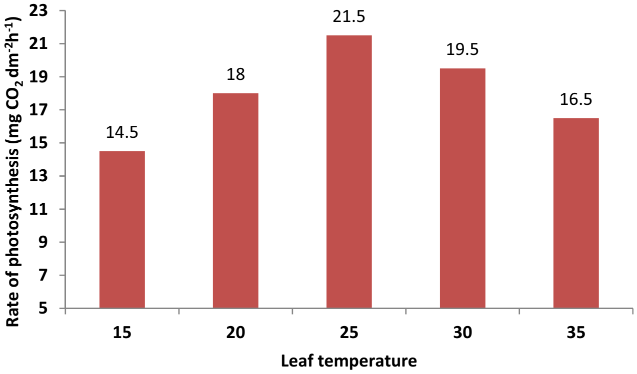

Fig. 3 Rate of photosynthesis vs leaf temperature (Source: Mahon et al. 1977)

Solar Radiation and Photoperiod

The crop growth increases with an increase in intercepted solar radiation in the leaf canopy and vice-versa (Iizumi and Ramankutty 2015; Jhajharia et al. 2018). Cassava reaches its full photosynthetic capacity only at a hot humid climate with high solar radiation (Gleadow et al. 2009). The flowering in cassava can be affected by changes in photoperiod (Keating et al. 1982), and the optimal photoperiod for cassava is found to be 12 h (Bolhuis 1966). Long day promote the growth of shoots and decrease storage root development, at the same time, short day increase storage root growth, and reduce shoots. Climate studies indicate a global decline in solar radiation (Yang et al. 2009; Jhajharia et al. 2018). The initiation and development of tubers depend on solar radiation, and hence shading can negatively influence crop growth (Fukai et al. 1984). Shading decreases shoots but increases plant height and the leaves tend to be adapted to low light conditions. However, field studies on cassava yield under shades indicate their adaptability in regions with variations in incoming solar radiation (Aresta and Fukai 1984; Nedunchezhiyan et al. 2012). Similarly, limited literature is available in case of the influence of UV-B on cassava. Ziska et al. (1993) indicate a significant reduction in root weight (32%) due to the impact of UV-B, even though further research is needed to make a generalized conclusion.

Air Humidity, Vapour Pressure Deficit and Soil Water Stress

Prolonged drought results in low air humidity with higher air vapour pressure deficit (VPD). The inherent mechanism of

Table 2 Temperature and growth stages of cassava

Temperature (°C)	Growth stages
<18 or > 37	Sprouting impaired
28.5–30	Sprouting faster (optimum)
<15	Plant growth inhibited
16–38	Cassava can grow
25–29	Optimum for plant growth
<18	Reduction in leaf production rate, total and root dry weight
20–24	Leaf size and leaf production rate increased; leaf life shortened
28	Faster shedding of leaves, reduction in no of branches
25	Highest photosynthesis in controlled chambers
30–35	Maximum photosynthesis (90–100%)
30–40	Highest rates of photosynthesis in the field
16–30	Transpiration rate increases linearly and then declines

(Source: Manrique 1992; Alves and Setter 2000; Ravi et al. 2008)

cassava to adapt changes in air humidity, as well as soil water deficits, makes this crop suitable for a wider range of climatic conditions. Studies indicate that cassava is sensitive to air humidity and it is better explained in terms of the presence of a large number of stomata (>400 stomata mm^{-2}) in the leaves (El-Sharkawy and Cock 1984a; El-Sharkawy and Cock 1984b; El-Sharkawy et al. 1985). Stomata tend to close under higher VPD, i.e., under dry air conditions. Wind can also intensify the stomata closure due to higher VPD and stomata closure is highly observed under upwind leaves compared to the downwind leaves (less exposed leaves) due to the reduced moisture boundary (El-Sharkawy 1990). The uptake of CO_2 and water loss is also decreased during higher VPD with reduced leaf conductance by partial closing of stomata without affecting the leaf potential as well as rate of photosynthesis by slow depletion of available soil water and the heliotropic response of leaves reduces the energy interception during mid-day (El-Sharkawy and Cock 1987; El-Sharkawy 1990; Calatayud et al. 2000). In addition, there observed a strong correlation between leaf conductance/ yield and VPD/ air humidity, and the biomass and root yield increases in the humid environment due to higher leaf photosynthesis (El-Sharkawy and Cock 1987, 1994). Similarly, a decrease in air humidity causes a decline in canopy conductance and transpiration (Oguntunde and Alatise 2007). However, the air humidity can be increased by artificial misting, and studies indicate an increased dry matter production under the application of artificial misting (El-Sharkawy and Cock 1987).

The prolonged dry periods cause plants to adapt themselves by changing physiological characteristics. Stomatal closure is the primary adaptation of plants to water stress by reducing guard cell's turgor without affecting the rate of photosynthesis (Yamaguchi-Shinozaki and Shinozaki 2006; Ceballos et al. 2011; Osakabe et al. 2014). Also, the accumulation of epicuticular wax over the leaf covers stomatal pores in cassava and enhances its resistance to water stress (Zinsou et al. 2006). Experimental reports indicate the leaf drooping or folding property of cassava reduces transpiration with a reasonable photosynthetic rate. This phenomenon in cassava mitigates the water stress and makes the crop tolerant to prolonged drought (El-Sharkawy 2004, 2007). The rate of leaf formation also decreases during prolonged dry periods with the abscission of existing leaves (El-Sharkawy 2004; Liao et al. 2016). During water stress conditions, the PEP (phosphoenolpyruvate carboxylase) activity is higher and the activity of RUBP (Ribulose bisphosphate) is reduced to around 42%, and this makes cassava an intermediary plant of C_3-C_4 group. This higher PEP activity enhances its resilience to water stress by reducing photorespiration (El-Sharkawy 2006). Water stress induces more abscisic acid (ABA) in the leaves and they decrease the rate of leaf area growth (Alves and Setter 2000). Cassava has a higher photosynthetic rate immediately after the recovery of water stress with higher leaf nutrient content (El-Sharkawy et al. 1993; El-Sharkawy 2007; Ravi et al. 2008). Cassava can also maintain a photosynthetic rate of 50% during prolonged drought condition, and this makes cassava adaptable to the changing climatic conditions (Ravi and Saravanan 2001).

The fine root system of cassava is another factor that makes this crop tolerant to water stress. The fine root system of the crop can penetrate to a depth of 2 m, hence it can exploit water at deeper soil layers (hydraulic lift) with low depletion rate, and hence it increases seasonal crop's water use efficiency (Alves and Setter 2000; El-Sharkawy 2004, 2007). Also, cassava can shift its optimum temperature to a higher level and thereby reduces its water requirement for growth stages (Long 1991; El-Sharkawy 2014). Studies also indicate that aquaporin genes in cassava are down-regulated during water stress, as they are highly responsible in stomatal opening and closing. Aquaporins, the intrinsic protein family transports water across the cell membrane and regulates the movement of water in response to osmotic gradients (Yu et al. 2016; Luang and Hrmova 2017). By regulating aquaporin, the water loss due to transpiration reduces with the closure of stomata (Khan et al. 2015; Putpeerawit et al. 2017). Similar results are reported by Zhang et al. (2008). During water stress conditions, the plant reduces the production of shoot biomass and however, there is not much reduction in root biomass with higher harvest index (storage root yield/total biomass) values. This ability is observed only in cassava and not with other major staple food grain crops (Connor et al. 1981; El-Sharkawy and Cock 1987). Some studies also indicate the negative influence of continuous drought on leaf area, shoot and root dry matter production in cassava (El-Sharkawy and Cadavid 2002). Supplementary irrigations can mitigate this influence, which increases crop yield (Shanmugavelu et al. 1973). However, the resilience level of cassava changes from one variety to another (De Carvalho et al. 2016).

Salinity

Agricultural salinity leads to osmosis and the available plant root water is transferred to the soil, which affects crop growth and yield, especially the leaf hydration. Limited studies are conducted on the sensitivity of cassava to salinity. In a study, cassava plants tested in vitro has increased the biomass production with a salinity level of up to 20 millimoles L^{-1} (mM) of NaCl and in vitro cassava can tolerate up to 25.66 mM of NaCl (Carretero et al. 2007; Cheng et al. 2018). However, this resilience changes from one variety to another (Hawker and Smith 1982; Shannon and Grieve 1999; Carretero et al. 2007) and a level of above 20 mM causes a reduction in the crop yield (Cruz et al. 2017). Advancement of biotechnology can also enhance cassava production in dry areas with salinity to cope with the future food demand. In a study, Carretero et al. (2008) indicate the tolerance level of cassava is increased to a level of 136.8 mM by arbuscular-mycorrhizal, AM (Azcon and Barea 1997) colonization by Glomus intraradices. Gleadow et al. (2016) also indicate that NaCl levels of up to 100 mM did not cause much reduction in the tuber mass of already established cassava, and they can tolerate up to 150 mM of NaCl, but the younger ones can tolerate up to 40 mM of NaCl.

Elevated Ozone

Ozone (O_3) is a greenhouse gas and is a major source of air pollution. Climate projections indicate an increase in the level of O_3 as part of climate change (IPCC 2013; Ainsworth et al. 2012). Ozone reduces leaf area index, photosynthesis, and increases senescence and finally reduces the crop yield (Ainsworth et al. 2012; Ainsworth 2017). O_3 (minimum amount of 80 ppb) causes a rapid reduction in stomatal conductance (Vahisalu et al. 2010) and then a full recovery is observed within 30 to 40 mins (Kollist et al. 2007). Studies also report that the sensitivity of stomata to abscisic acid is compromised with elevated O_3 (Wilkinson and Davies 2009, 2010). The study by Feng et al. (2008) and Tai and Martin (2017) indicate elevated ozone reduces stomatal conductance in one of the root crops potatoes with a yield reduction of 0.3% compared to other sensitive crops. The ozone impact on major food grains is higher and the expected loss due to the reduction in their production is 14–26 billion US dollars (Van Dingenen et al. 2009). Senescence reducing genes (*ipt*) is available in the case of cassava (Zhang et al. 2008) and this gives the scope of further studies on cassava breeding for its resilience to the elevated O_3 (Ainsworth et al. 2012).

Elevated CO_2

Studies on climate change indicate an increase in the level of present atmospheric CO_2 and this will reach a value of 1000 ppm by 2100 (IPCC 2013; Meehl et al. 2007). This increase in CO_2 concentrations can influence photosynthesis and thereby the growth stages and the yield of plants (Ziska 2008). Based on photosynthetic properties, i.e., the formation of carbon compounds during photosynthesis, the plants are classified as C_3 and C_4. Cassava comes under C_3 plants based on physiological and photosynthetic characteristics (Edwards et al. 1990). Even though cassava is a C_3 crop, the higher PEP activity compared to other C_3 crops makes cassava an intermediary plant of C_3-C_4 groups and hence cassava is superior to other C_3 crops under different environmental conditions (El-Sharkawy 2006). The elevated CO_2 enhances the net photosynthetic CO_2 uptake (Fig. 4), which results in an increase in dry matter production and yield in cassava (Jia et al. 2015; Cruz et al. 2016; Kimball 2016). Under elevated CO_2, the potential yield of cassava will reach up to 50 t ha^{-1} with the availability of water and nutrients (Lebot 2009).

Sink (tissues that use or store carbohydrate) duration is one of the limiting factors controlling photosynthesis. In tuber crops, sinks last throughout the season compared to the major food crops sinks. This makes cassava better adapt to the elevated CO_2 (Rosenthal and Ort 2012) and hence they have

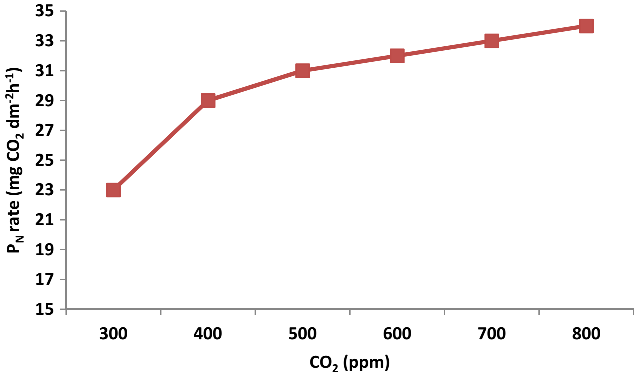

Fig. 4 Rate of photosynthesis under elevated CO_2 (Source: Mahon et al. 1977)

higher harvest index compared to the other grain crops (De Temmerman et al. 2007). Also, compared to the grain crops, tubers are already stable for the support of root structure, and they don't require any additional investments in supporting the accumulated photosynthate which enhances the production of tubers under elevated CO_2 than grain crops (Imai and Coleman 1983). The instantaneous transpiration efficiency for cassava is also reported as higher (up to 83%) in case of elevated CO_2 (De Kauwe et al. 2013; Cruz et al. 2016). These all indicate elevated CO_2 has a positive impact on the root yield of cassava (Gabriel et al. 2014).

The elevated CO_2 reduces stomatal conductance by 30 to 60%, which improves leaf-water use efficiency, and hence better plant growth for cassava during water deficit conditions (Ainsworth and Long 2005; Morgan et al. 2011; Barton et al. 2012). Studies report a reduction in evapotranspiration in the presence of elevated CO_2 by 10% (Kimball 2016), and this increases the water use efficiency of the crop. In a study, Ravi et al. (2008) report that elevated CO_2 increased the water use efficiency from 3.3–4.5 to 10.5–17.1 mg CO_2 g H_2O^{-1}. The elevated CO_2 can stimulate photosynthesis, even during severe water stress conditions (Warren et al. 2011; Bauweraerts et al. 2013). A higher photosynthetic rate under water stress conditions enhances dry matter production (Cruz et al. 2016; Thinh et al. 2017). Elevated CO_2 increases carbon allocation to root growth, and this augments carbon assimilation during water scarcity (Iversen 2010).

The increase of CO_2 from 390 to 750 ppm in irrigated plants resulted in a 20% increase in dry matter production. The percentage increment in the case of water deficit condition is reported as 61% (Cruz et al. 2016). This indicating the influence of elevated CO_2 is predominant in the case of water stress conditions. A similar conclusion is provided in a study by Poorter and Pérez-Soba (2001) in the case of herbaceous species. These all results indicate that elevated CO_2 can mitigate the impact of drought to an extent and total dry matter produced was higher compared to the plants under good water availability (El-Sharkawy 2014; Cruz et al. 2016). Elevated CO_2 also promotes fine root growth (Iversen 2010) in the deeper soil layers and hence they can extract water from deeper layers of soil and can withstand drought (Aresta and Fukai 1984).

Literature also shows elevated CO_2 can rectify the issues due to the limited solar radiation. During the low-light period, the growth is mainly limited by the low availability of carbon. Hence, the limited growth under low solar radiation can be compensated with elevated CO_2 (Kimball 1986; Idso and Idso 1994; Poorter and Pérez-Soba 2001).

Temperature and Elevated CO_2

Studies show that the combination of elevated CO_2 and optimum temperature together can further enhance crop growth. The crop dry matter production is highest with optimum temperature, elevated CO_2 than at lower temperatures, and elevated CO_2 (Curtis and Wang 1998; Poorter and Pérez-Soba 2001). Elevated CO_2 increases the rate of photosynthesis by increasing the concentration of the substrate and by reducing the oxygenation (Long 1994). The solubility of CO_2 decreases faster at high temperatures and this reduces the relative abundance of CO_2 in the chloroplasts (Jordan and Ogren 1984). Hence, the effect of elevated CO_2 is higher under warm temperatures than cold conditions (Poorter and Pérez-Soba 2001; https://www.fao.org). The elevated CO_2 helps cassava to adjust the canopy temperature by decreasing the stomatal conductance and evapotranspiration. This leads to reductions in cooling effect on leaves, and this results in an increase in canopy temperature to about 0.4 to 1.7 °C provided sufficient availability of water and nutrients (Kimball 2016).

Salinity and Elevated CO_2

As previously stated, the elevated CO_2 reduces stomatal conductance without affecting the rate of photosynthesis. If transpiration increases, the rate of uptake of saline water into the plant also increases. Therefore, with reduced stomatal conductance, the elevated CO_2 can mitigate the impact of salinity to an extent (Schwartz and Gale 1981). Arp et al. (1993) reported that in the C_3 group (Sedge *Scirpus*), elevated CO_2 enhances the salinity tolerance level. This result supports the possibility of wider cultivation of cassava in arid as well as semi-arid regions to meet the future food demand. However, further studies are needed to identify the extent of this positive impact of elevated CO_2 on the resilience of cassava to soil salinity (Yeo 1999).

Resilience to Biotic Stresses

The wider agro-ecological adaptability of cassava can cause the development of different biological problems such as diseases and pests attack. Cassava has the property of cyanogenesis, i.e., the ability to generate hydrogen cyanide (HCN), and this acts as a defense mechanism against pathogens, arthropods, and mammalian pests. The cyanogen contents in the root also act as a hindrance to the burrowing bugs (Mutisya et al. 2013; Parsa et al. 2015a, 2015b). The changes in the climatic conditions can also enhance the growth of these pests and Bellotti et al. (2012) indicate a projected positive trend is observed for these pests in Southeast Africa, Madagascar, Coastal India, and Southeast Asia. This indicates an extensive study is needed in cassava breeding for higher resistance to these pests in these locations. Other than the pests, cassava mosaic disease (CMD), cassava brown streak disease (CBSD), and cassava bacterial blight are some of the common diseases of cassava (Campo et al. 2011). Studies are going on cassava breeding for its resistance to such viral diseases as viral attacks severely reduce the crop's yield (Carabalí et al. 2010; Legg et al. 2011). In a recent study, Nzuki et al. (2017) clearly illustrated the cassava breeding for its resistance to diseases and pests in Tanzania. They identified some varieties (e.g. Kiroba and Namikonga) that are resistant to diseases and pests. This supports the scope of the resilience of cassava to biotic stresses and the higher possibility to develop resilient varieties for future food security. Studies also indicate the geographic locations where the pests of cassava grow suitably in the context of climate change (Lu et al. 2014; Parsa et al. 2015a, 2015b). They may help decision-makers to select suitable site-specific pest management practices for cassava.

Climate Suitability of Cassava

A few studies are also conducted to identify the climate suitability of cassava in the context of changing climatic variables (Kamukondiwa 1996; Ceballos et al. 2011). Liu et al. (2008) analyzed the climate change impact on cassava, maize, wheat, sorghum, rice and millet in Africa, and concluded that yield variations are least for sorghum and cassava compared to other crops. Ray et al. (2019) also support this statement. Jarvis et al. (2012) also indicated that positive impacts are observed for the climate suitability (−3.7 to 17.5%) of cassava in Africa compared to other major food crops such as beans (−16% ± 8.8), banana (−2.5 ± 4.9), potato (−14.7 ± 8.2), and sorghum (−2.66 ± 6.45). A similar study is conducted by Sabitha et al. (2016) in India to check the suitability of cassava over the present cassava growing areas of India for the near future, 2030. They also showed a significantly positive impact on climate suitability with a percentage of −2.2 to 15%. In a study, Mupakati and Tanyanyiwa (2017) also recommend the adaptation of cassava in Zimbabwe in the changing climate. In a study, Heumann et al. (2011) indicate cassava's suitability in uplands compared to low lands, as well as its suitability towards the south and southwest area of the study location in Thailand. This shows the possibility of shifting its suitability towards higher elevations, and more studies are needed to make generalized statements. In conclusion, as a solution to climate change impact on other major food grain crops, cassava can be extended in more areas in addition to the current growing areas worldwide due to its resilience and adaptation characteristics (Lobell et al. 2008; Schenkler and Lobell 2010; Sabitha et al. 2016), and this will enhance its production in the context of food security.

Conclusions

Climate change studies indicate a diminishing trend in the production of major food grain crops, and this demands agricultural experts to enhance the cultivation of climate-resilient food crops, which can act as an alternative for these grain crops. Among climate-resilient crops, cassava (*Manihot esulenta* Crantz) is getting much attention and now it has become the fifth major producing food crops in the world other than Maize, rice, wheat, and potato (FAO 2013). Studies indicate a tremendous reduction in the yield of major grain crops by 2050 and this production gap can be bridged by cassava, the major tuber crop (Bedoussac et al. 2015; De Souza et al. 2017). Cassava can cultivate over a wider range of climatic as well as soil conditions irrespective of the other grain crops. The review of 136 published articles is carried out to understand the physiological characteristics as well as the yield of cassava in the context of changing climate. The variations in the growth and yield of cassava with projected temperature, solar radiation, air humidity and soil water stress, salinity, elevated ozone and CO_2, combined effects of CO_2 and temperature, CO_2 and salinity, biotic resilience of cassava followed by its climate suitability are analyzed. Studies highly recommend the adaptability of cassava in regions with higher temperatures and it can tolerate up to 40 °C (El-Sharkawy et al. 1984b; Ravi et al. 2008). However, significant yield reductions are observed with temperatures >40 °C (El-Sharkawy et al. 1984b). Climate studies indicate a declining trend in the sunshine, but cassava cultivation can be extended to regions with higher variations in solar radiation without much compromise in its yield (Nedunchezhiyan et al. 2012). The prolonged drought due to climate change enhances soil salinity, and already established cassava can grow up to a level of 150 mM, but the tolerance level of younger ones is limited to 40 mM (Gleadow et al. 2016). The advancement of biotechnology on cassava can also improve its tolerance to salinity (Carretero et al. 2008). Compared to other crops, cassava has an inbuilt mechanism to tolerate water stress by leaf drooping as well as by partial closing of stomata. This results in reduced transpiration, without much influence on the rate of photosynthesis (Calatayud et al. 2000; El-Sharkawy 2004, 2007).

As cassava belongs to the intermediate level of C_3-C_4 groups, the elevated CO_2 (up to 700 ppm) increases the photosynthetic efficiency compared to the C_3 groups, and this further improves the ability of cassava to tolerate water stress (Cruz et al. 2016) and salinity (Arp et al. 1993). The combined effect of elevated CO_2 and higher temperatures also enhance the growth and yield of cassava (Rawson 1992; Curtis and Wang 1998; Poorter and Pérez-Soba 2001). The biotic resilience of cassava is also giving its scope as a future insurance crop as it already indicates its resilience to abiotic stresses. The climate suitability studies also highlight its wider adaptability irrespective of the agro-climatological conditions. A shifting of cassava's suitability towards higher elevations is also reported and further studies are needed in this area to make generalized statements. In summary, cassava is tolerant of abiotic stresses in the context of changing climate (Jarvis et al. 2012, Sabitha et al. 2016) and it can bridge the future food demand gap.

Research Gap

The major findings of this review for future research are listed here one by one. Literature is available for the drought resilience of cassava. Research articles are also available in case of the influence of meteorological variables on cassava in the context of climate change. However, research deficit is observed in the case of elevated ozone tolerance of cassava. The research gap is also observed under the area of salinity tolerance of cassava. This study recommends an extensive study on this issue as we need to increase the agricultural land area to meet the food demand-supply gap (Ladeiro 2012). Studies also needed in combination with biotechnology to derive varieties with genes, which have a high tolerance to biotic stresses such as pests and diseases (Zhang et al. 2008; Ceballos et al. 2011). Out of a few climate suitability studies, all are for African as well as Indian context. More studies are needed to identify any significant shift/increase in the global level production of cassava.

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Compliance with Ethical Standards

Conflict of Interest The authors declared that we have no conflict of interest.

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