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Salinity effects on rice, rice weeds, and strategies to secure crop productivity and effective weed control. A review

Nicholas E. Korres¹ · Dimitra A. Loka² · Thomas K. Gitsopoulos³ · Vijaya K. Varanasi⁴ · Demosthenes Chachalis⁵ · Andrew Price⁶ · Nathan A. Slaton⁷

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Abstract

This study is the first one that examines simultaneously the direct and indirect effects of soil salinity on rice and rice weeds and suggests solutions to secure both rice production and effective weed control. Salinity negatively impairs growth, reproduction, and rice grain yield. Several studies have addressed the effects of salinity on rice yield when plants are exposed to salinity stress either at the vegetative or reproductive stage. However, rice response to salt stress is a quantitative trait that is influenced by several other factors including genotype, severity and extent of stress, type of tissue, and the stage of growth at which the stress occurs. It is therefore important to exploit holistically the effects of salinity on rice in order to utilize effective short- and long-term strategies to alleviate the negative effects of salinity on the crop. The complexity of this important and growing problem becomes even more acute when the effects of rice weeds that coexist with the crop at saline conditions are taken into consideration. Although the response of rice to salt stress has been investigated in-depth, knowledge of the salinity effects on the weed community is limited. Furthermore, the synergistic options for both salinity and weed management are inadequate. Here, we suggest strategies that address both issues. The use of salt-tolerant rice cultivars, transplanting systems, and seed priming can be adequately employed for both salinity adaptation and effective weed control. Other strategies such as double rice cropping systems, fertilization management, use of soil amendments, water management, exogenous application of phytoprotectants, or inoculation with growth-promoting bacteria require more research and thorough consideration before their adoption because it is likely that such practices could benefit the crop as well as the weeds.

Keywords Rice growth · Rice production · Soil salinization · Salinity adaptation · Weed management

Contents

1. Introduction
2. Effects of salinity on rice
 - 2.1 Effects of salinity on rice biochemistry
 - 2.2 Effects of salinity on rice physiology
 - 2.3 Effects of salinity on rice morphology
 - 2.4 Effects of salinity on rice seed germination
 - 2.5 Effects of salinity on rice yield and yield components
3. Effects of salinity on rice weeds
 - 3.1 Effects of salinity on rice weeds biochemistry and physiology
 - 3.2 Effects of salinity on weed germination
 - 3.3 Effects of salinity on weed biological characteristics
 - 3.4 Effects of salinity on weed population dynamics
4. Short-term strategies to alleviate the effects of salinity and weed interference on rice crop

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- 4.1 Selection of salt-tolerant rice cultivars that can compete with weeds
- 4.2 Seed priming
- 4.3 Transplanting
- 4.4 Exogenous application of minerals and the use of fertilizers
- 4.5 Use of soil amendments
- 4.6 Irrigation and use of mulches
- 4.7 Chemical weed control
- 4.8 Miscellaneous tactics against salinity and weeds
 - 4.8.1 Double-rice cropping system
 - 4.8.2 Scraping soil surface, pre-irrigation, hand weeding
 - 4.8.3 Use of halophytes in rotation
 - 4.8.4 Fish and rice co-culture
- 4.9 Exogenous application of phytoprotectants
- 4.10 Inoculation with growth-promoting bacteria and endophytes
5. Long-term strategies to alleviate salinity effects in rice crops
 - 5.1 Genetics of salt tolerance and development of salt-tolerant cultivars
 - 5.1.1 Approaches for the development of salt-tolerant rice cultivars
 - 5.2 Salinity management and climate change
6. Synthesis and future research
- References

1 Introduction

Rice (*Oryza sativa* L.) is an important staple crop that is consumed by more than half of the world's population (Khush 2005). Increases in rice productivity through improvements in crop management, effective weed control and use of cultivars tolerant to abiotic stress will secure higher yield production, therefore satisfying present and future rice demands (Chauhan et al. 2013). Rice is the only staple crop that can be established and grow well in waterlogged environments. However, it is relatively sensitive to salinity with a saturated paste electric conductivity (EC_{SPE}) threshold of 3 dS m^{-1} compared to rye (*Secale cereale* L.), the most tolerant cereal to salinity, with an EC_{SPE} threshold of approximately 11 dS m^{-1} (Maas 1993). A soil is considered saline when it exhibits an EC_{SPE} value greater than 4 dS m^{-1} (Rengasamy 2006) (equivalent to approximately $40 \text{ mmol L}^{-1} \text{ NaCl}$) (Ghosh et al. 2016) with an osmotic pressure of approximately 0.2 MPa and pH between 7 and 8.5 (Mengel et al. 2001). A saline soil is the reservoir of a number of soluble salt ions including Ca^{++} , Mg^{++} , Na^+ , SO_4^{2-} , Cl^- , HCO_3^- , with potentially exceptional amounts of K^+ , CO_3^{2-} , and NO_3^- (Ghosh et al. 2016) (Fig. 1). However, salinity in these environments is often linked to sodicity that determines the excess amounts of soil Na^+ with consequent severe phytotoxicity effects on crops (Shi and Wang 2005).

Soil salinity represents an important and growing problem to crop production worldwide in particular, but not exclusively, to irrigated areas where salinization is expected to increase due to climate change and injudicious irrigation practices (Munns and Tester 2008). Particularly, salinity occurs in coastal areas due to contamination of the aquifer by sea water. Currently, salt-affected areas occupy approximately 900 Mha (Munns 2005), which represent approximately 6% of the world's land or 20% of cultivated land and 20–30% of the world's irrigated areas (Shrivastava and Kumar 2015; Qadir et al. 2014). According to Anosheh et al. (2011) and Emam et al. (2013), salinity-affected areas will increase to more than 50% of the world's total arable land by 2050 if measures are not taken to prevent it, with subsequent reductions in plant growth and productivity, hence food production (Ashraf et al. 2015). Rice yield is significantly reduced under salinity stress with an annual estimation of 30–50% yield losses (Eynard et al. 2005). In parallel, weeds can cause significant yield losses in rice through their competition for light, water, and nutrients (Korres 2018). Rodenburg and Johnson (2009) reported yield losses between 28 and 74%, 28 and 89%, and 48 and 100% for transplanted, direct-seeded, and upland rice, respectively. The aim of this review paper is to suggest short and long-term solutions for securing rice yield while enhancing the effectiveness of weed management tactics under salinity stress. A prerequisite to achieving our aim is to underline the effects of salinity on rice and rice weeds at the biochemical, physiological, and morphological levels.

2 Effects of salinity on rice

2.1 Effects of salinity on rice biochemistry

At the biochemical level, alterations of osmolytes concentration in the cytoplasm have been often found in salt-stressed plants (Kanawapee et al. 2012; Ishikawa and Shabala 2019). Decreases in carbohydrate levels in rice leaves and shoots, for example, have been widely reported under salt-stress conditions (Sultana et al. 1999; Abdullah et al. 2001). On the contrary, Djanaguiraman et al. (2006), Roychoudhury et al. (2008), and Boriboonkaset et al. (2013) observed increases in leaf sugars in salt-tolerant cultivars under salt stress conditions. The accumulation of sugar content in rice roots is less disputable as most of the research has shown an increase in the levels of soluble carbohydrates in the roots of rice plants grown under salt stress (Nemati et al. 2011; Siahpoosh et al. 2012; Nam et al. 2015). Likewise, the level of polyols and trehalose, a non-reducing disaccharide, tend to increase under salinity stress, especially in salt-tolerant cultivars (Abdelgawad et al. 2014; Zhao et al. 2014; Mostofa et al. 2015) possibly as a defense mechanism against salinity stress (Zhao et al. 2014). Proline contributes to the maintenance of



Fig. 1. A salt-affected soil (courtesy N. E. Korres)

the osmotic balance under conditions of salt or drought stress (Roychoudhury et al. 2008). It participates in several processes including protection of enzymes, membranes, and cellular structures, detoxification of free radicals, and serves as a nitrogen source compound during periods of inhibited growth (Hong et al. 2000). Proline level in leaf, shoot grain, and panicles increases under salt stress conditions (Sultana et al. 1999; Mostofa et al. 2015; Rahman et al. 2016; Gerona et al. 2019) especially in salt-tolerant rice cultivars (Fig. 2) (Chutipajit et al. 2011; Roychoudhury et al. 2011; Gerona et al. 2019) although Saleethong et al. (2013) reported the same trend for salt-sensitive cultivars.

Salinity stress also results in the overproduction of reactive oxygen species (ROS) due to decreases in stomatal conductance, electron transport, and accumulation of toxic ion concentrations (Demiral and Turkan 2006), especially in salt-sensitive cultivars (Ghosh et al. 2012; Khare et al. 2015). In order to attenuate membrane instability due to the production of ROS, plants have developed elaborate antioxidant defense systems consisting of enzymatic and non-enzymatic

antioxidant production (Gill and Tuteja 2010). However, response to salinity through antioxidant production is variable among rice genotypes depending on their scavenging potential (Munns and Tester 2008), the extent and severity of salt stress (Islam et al. 2017), and the rice growth stage at which the stress occurs (Moradi and Ismail 2007).

Research on rice under salt-stress conditions indicated that salt-tolerant cultivars were able to maintain their membrane integrity due to the high levels of membrane-bound polyamines (PAs) (Roy et al. 2005). Ghosh et al. (2012) reported that salt stress increased the levels of bound-PAs in salt-tolerant, compared to salt-sensitive, rice cultivars although significant variability of individual free PAs has been observed depending on rice genotype, the type of tissue, and rice growth stage (Roy et al. 2005; Ndayiragije and Lutts 2007; Roychoudhury et al. 2011; Do et al. 2014). Responses of plants to salt stress conditions induce alterations in gene expression and consequently changes in protein synthesis. Early reports indicated that abscisic acid (ABA)-responsive proteins were expressed under conditions of salt stress in rice

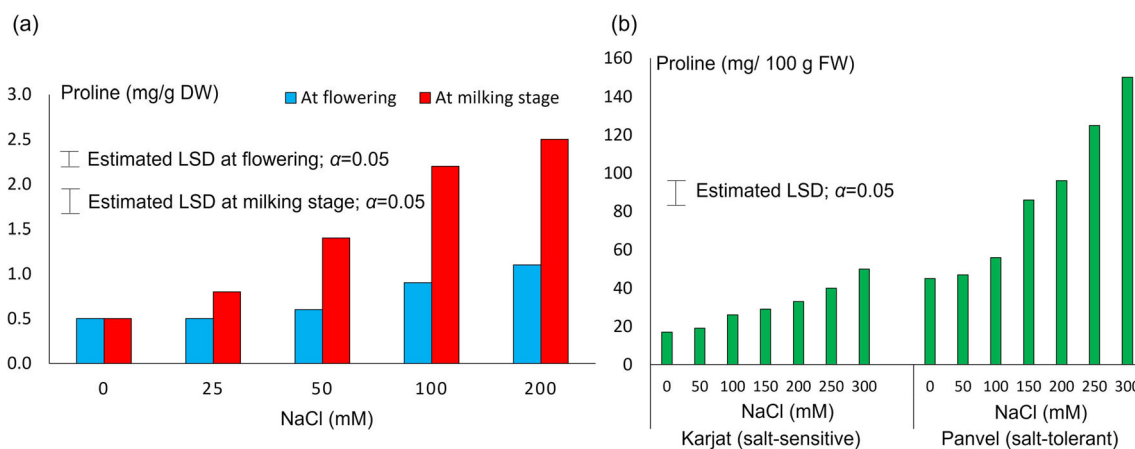


Fig. 2. Effects of salinity on proline content in (a) leaves at different stages and in (b) roots of salt-sensitive and salt-tolerant rice cultivars. Figure on the left (a) is based on Sultana et al. (1999), salinity stress of 75-day old rice plants of cv. Koshihikari, for 15 days at the flowering and milking stages. Figure on the right (b) is based on Kumar et al. (2008), where 14-day-old rice plants were exposed to salinity stress for 7 days. DW, dry weight (the weight, usually in grams, recorded after drying plant

tissue at temperatures higher than ambient temperature. This process eliminates water from the plant); FW, fresh weight (fresh biomass production that includes water content in the plant tissue), LSD, least significant difference. LSD is a statistic that is used to separate means between treatments at a particular level of statistical probability as determined by the analysis of variance

roots with greater quantities in the salt-tolerant than in salt-sensitive cultivars (Moons et al. 1995). Since then, several salt-responsive proteins including ABA, ascorbate peroxidase, and caffeoyl CoA O-methyltransferase have been reported (Salekdeh et al. 2002). The expression of these proteins was found to be variable and dependent on the type of tissue, the extent and the duration of salt stress (Abbasi and Komatsu 2004), or their association with primary metabolic processes such as photosynthesis, photorespiration, ATP synthesis, nitrogen metabolism, and adaptation (Kim et al. 2005; Frukht et al. 2020).

2.2 Effects of salinity on rice physiology

The negative effects of salinity on rice photosynthesis (PS), chlorophyll, carotenoid, and mineral contents along with disruptions in water relations and root hydraulics are well documented (Quinet et al. 2010; Pires et al. 2015; Meng and Fricke 2017). Stomatal and non-stomatal limitations (Cha-um et al. 2009; Wang et al. 2018), decreases in leaf protein content (e.g., Rubisco) (Sultana et al. 1999; Wang et al. 2018), and reduced availability of CO₂ at carboxylation sites (Djanaguiraman et al. 2006; Boriboonkaset et al. 2013; Wankhade et al. 2013b) are the main reasons for reduced PS efficiency in rice plants grown under salt-stress. In addition, increases in non-photochemical quenching (NPQ) vs. photochemical quenching (qP) of chlorophyll fluorescence in IR29, a salt-sensitive rice cultivar, compared to Pokkali, a salinity-tolerant rice cultivar (Fig. 3) (Lee et al. 2013) indicate reduced photochemistry in the former. Moradi and Ismail (2007) also observed increases in NPQ with simultaneous decreases in the electron transport rate, a measure of the quantum yield in PS II, when sensitive rice cultivars were exposed to salt stress in comparison to salt-tolerant rice cultivars including rice cultivar Pokkali.

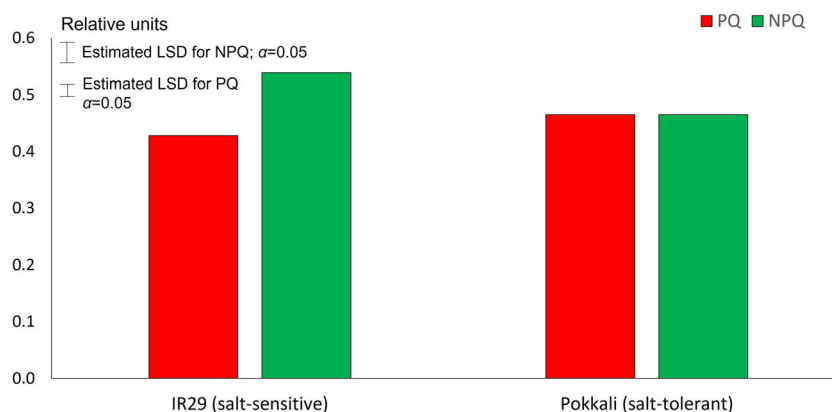


Fig. 3 Effects of salinity on rice photochemistry. PQ, photochemical quenching; NPQ, non-photochemical quenching. Based on Lee et al. (2013) where 24-day-old rice plants were exposed at 100 mM EC for 7 days. EC, electrical conductivity (EC is a measure of the “total salts”

Another important factor for reduced photochemistry in rice cultivars grown under salt stress is chlorophyll reduction (Lutts et al. 1996; Sultana et al. 1999; Amirjani 2011; Mostofa et al. 2015; Rahman et al. 2016) as time and salinity levels increases (Fig. 4) mostly due to disruptions in chlorophyll synthesis, increased degradation of chlorophyll, or oxidative damage and consequent destruction of chloroplasts (Rahman et al. 2000; Yamane et al. 2009). There is a positive correlation between chlorophyll content and Mg uptake (Lutts et al. 1996). Therefore, lower Mg uptake, under salt stress, could be another reason for chlorophyll content reductions. On several occasions, chlorophyll reduction was prominent in the salt-sensitive rice cultivars (Demiral and Turkan 2005; Roychoudhury et al. 2008; Wankhade et al. 2013a; Boriboonkaset et al. 2013) although some authors have reported no changes in rice chlorophyll content either for salt-sensitive or salt-tolerant rice plants when these were exposed to salt-stress (Walia et al. 2005; Kanawapee et al. 2013). Furthermore, chlorophyll *a* (Chl *a*) and chlorophyll *b* (Chl *b*) contents vary under salt-stress conditions with greater and faster decreases being observed in Chl *b* compared to Chl *a* (Fig. 4) (Djanaguiraman et al. 2006; Kanawapee et al. 2012; Boriboonkaset et al. 2013), hence increases in Chl *a/b* ratio.

Carotenoids serve as a defense mechanism in plants against photo-oxidative damage (Ashraf and Harris 2013) hence reducing photosynthetic efficiency. Their important role can be jeopardized under salt-stress conditions due to carotenoid content decreasing with increasing salt concentration or salt-stress duration (Boriboonkaset et al. 2013; Rahman et al. 2016), especially in salt-sensitive cultivars (Demiral and Turkan 2005). On the contrary, increases in anthocyanin content observed under salt-stress conditions were positively correlated with the stabilization of photosynthetic pigments (Chutipajit et al. 2011), suggesting that anthocyanins hold a crucial role in the maintenance of the photosynthetic apparatus under conditions of salt stress.

concentration in the nutrient solution). LSD, least significant difference. LSD is a statistic that is used to separate means between treatments at a particular level of statistical probability as determined by the analysis of variance

Fig. 4 Effects of salinity on (a) total chlorophyll and chlorophyll *a/b* ratio at flowering and milking stage in rice and (b) total chlorophyll, chlorophyll *a* and chlorophyll *b* at 35 and 100 days after rice plants were exposed to salinity stress (Days After Treatment-DAT). Figure on the top (a) is based on Sultana et al. (1999) and figure at the bottom (b) is based on Sultana et al. (2002). Estimated least significant difference (LSD) values at $\alpha=0.05$ equal to 0.5 and 0.6 for total chlorophyll and 0.2 and 0.3 for chlorophyll *a/b* at flowering and milking stages respectively. LSD is a statistic that is used to separate means between treatments at a particular level of statistical probability as determined by the analysis of variance

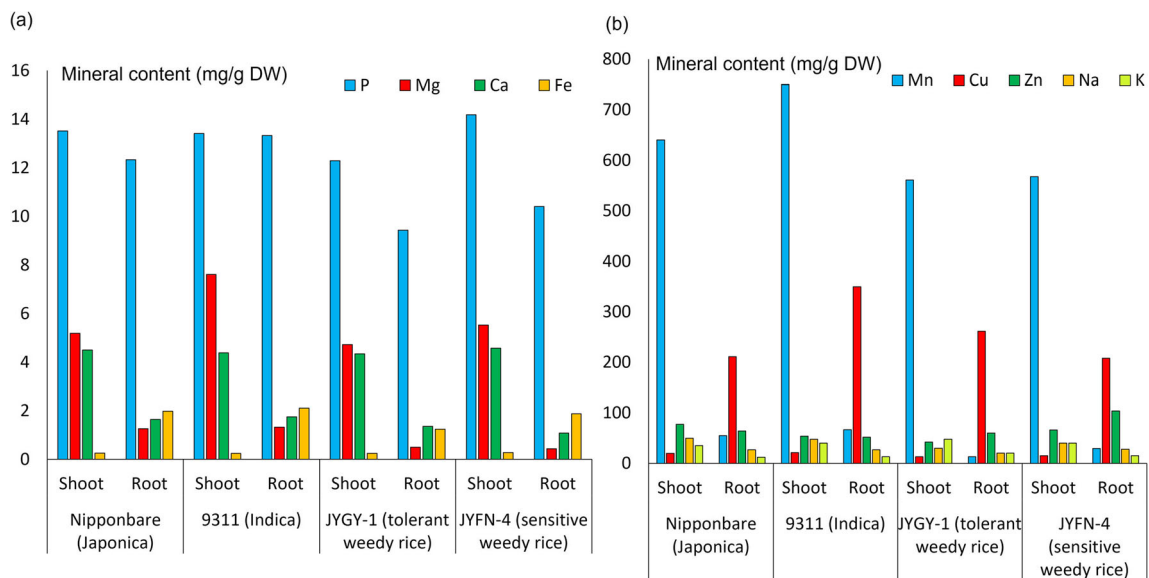
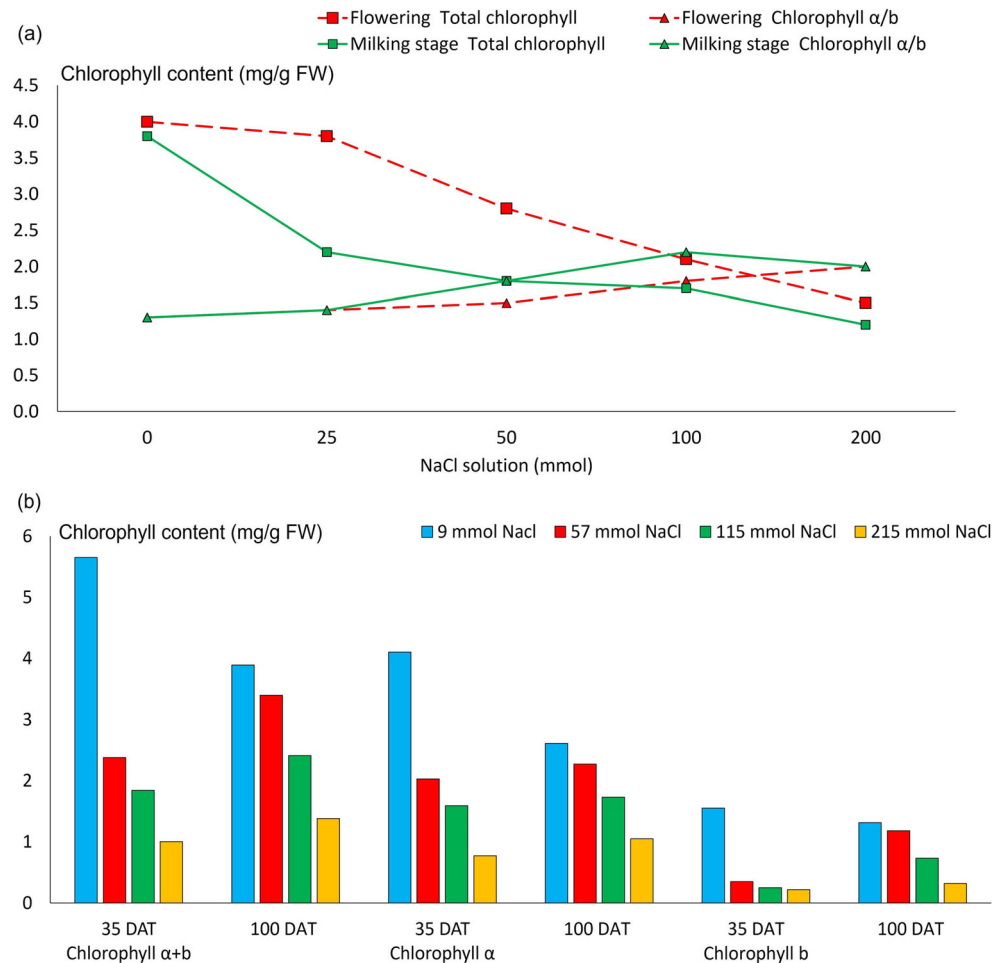


Fig. 5. Effects of salinity on the shoot and root rice mineral content of various rice cultivars including two lines of weedy rice with different salinity tolerance. Based on Zhang et al. (2018) where 14-day-old rice plants were exposed to 125 mM salinity stress for 7 days. DW, dry weight

(the weight, usually in grams, recorded after drying plant tissue at temperatures higher than ambient temperature. This process eliminates water from the plant)

Nutrient uptake and assimilation are greatly affected by salt stress (Fig. 5) (Kumar et al. 2008; Horie et al. 2012) since Na has been reported to compete with other cations such as K, Ca, Mg and Mn, while Cl ions have been observed to restrict NO_3^- and PO_4^- uptake (Munns and Termaat 1986; Romero et al. 1994). Disruptions in the uptake of other nutrients, including N, Fe, and Zn due to salinity have also been reported in the literature (Gupta and Huang 2014).

Reductions in shoot and leaf-N content with increasing salinity levels (Lutts et al. 1999; Abdelgawad et al. 2014) especially in salt-sensitive rice cultivars (Kumar et al. 2008) will decrease rice photosynthesis significantly.

In addition, differential responses on rice shoot-P content grown under salt stress have been reported (Kumar et al. 2008). However, Nemati et al. (2011) and Wang et al. (2018) have reported significant reductions in leaf-P content irrespective of the salt-tolerance level of the plant. Decreases in the shoot (Rahman et al. 2016; Zhang et al. 2018; Liu et al. 2019a) and leaf-K (Lee et al. 2011; Ghosh et al. 2012; Wang et al. 2013) contents as a result of increased shoot or leaf-Na content have also been recorded especially in salt-sensitive rice cultivars (Roychoudhury et al. 2008; Ghosh et al. 2012).

Concerning the secondary minerals such as Ca, variable results have been reported for root and shoot-Ca (Kumar et al. 2008; Rahman et al. 2016; Abdelgawad et al. 2014; Zhang et al. 2018). However, a consistent decreasing pattern has been reported for leaf-Ca (Sultana et al. 2002; Roychoudhury et al. 2008).

Substantial decreases in root- and shoot-Mg contents after exposure of rice plants to salt stress were reported by Nemati et al. (2011), Rahman et al. (2016), and Zhang et al. (2018). Likewise, reductions in root, shoot, and leaf-manganese (Mn) occur under conditions of salt stress (Sultana et al. 2002; Rahman et al. 2016; Zhang et al. 2018). Uptake of other micronutrients is rather complex due to the involvement of several factors (Grattan and Grieve 1999), although root and shoot iron and zinc have shown to decrease under salt-stress conditions (Kumar et al. 2008; Zhang et al. 2018).

2.3 Effects of salinity on rice morphology

Salinity causes reductions in leaf elongation rate, leaf length, and leaf width, irrespective of the genotype's growth habit, mostly due to changes in root water potential that result in poor leaf water supply and reduced turgor (Yeo et al. 1991; Roshandel and Flowers 2009; Wankhade et al. 2013a). In addition, reductions in the number of leaves and delays in leaf emergence have also been reported (Yeo et al. 1991) along with substantial reductions in leaf area (Akita and Cabuslay 1990; Amirjani 2010) due to the lower rate of leaf emergence and leaf growth in conjunction with the higher rate of leaf senescence (Munns 2005). Likewise, shoot growth inhibition, manifested as reductions in shoot height, fresh and dry weight,

is commonly observed under salinity, due to NaCl uptake, ion homeostasis disturbance, and reductions in leaf area which, is accompanied by reductions in photosynthesis and production of photoassimilates (Sultana et al. 1999; Cha-um et al. 2009; Razzaque et al. 2009; Amirjani 2011; Pires et al. 2015; Rahman et al. 2016;). Such decreases have been observed to be more prominent in the salt-sensitive than salt-tolerant genotypes (Demiral and Turkan 2006; Kumar et al. 2008; Quinet et al. 2010; Wankhade et al. 2013a; Boriboonkaset et al. 2013) and larger in *Japonica* than *Indica* cultivars (Lee et al. 2003; Liu et al. 2019a). On the contrary, root growth has been reported to be less sensitive to salt stress than shoot growth (Munns 1993) although reductions in water and mineral uptake under salt stress have caused root growth reductions, followed by decreases in root fresh and dry weights when rice plants exposed to salinity stress at various life stages (Neumann 1997; Roshandel and Flowers 2009; Quinet et al. 2010; Pires et al. 2015; Kibria et al. 2017; Liu et al. 2019a). Increases in the number of lateral roots have also been recorded to occur under conditions of salt stress as an adaptive response of rice plants to overcome root hydraulics decreases (Krishnamurthy et al. 2011).

2.4 Effects of salinity on seed germination

Several studies have demonstrated the negative effects of salinity on rice germination percentage (Table 1), germination index, germination rate, and mean germination time along with seedling establishment (Lutts et al. 1995; Zeng et al.

Table 1 Effects of salinity on the germination percentage of various rice cultivars. Twenty seeds for each cultivar were allowed to germinate under a range of salt solutions (NaCl) 4, 8, 12, or 16 dS m^{-1} salt concentrations including 0 dS m^{-1} (distilled water) as a control (based on Hakim et al. 2010). Estimated Least Significant Differences (LSD) at $\alpha=0.05$ for 0, 4, 8, 12, and 16 dS m^{-1} salt concentration equals to 4, 11, 24, 23, and 27 respectively. LSD is a statistic that is used to separate means between treatments at a particular level of statistical probability as determined by the analysis of variance

Cultivar	0	4	8	12	16
	% seed germination				
IR 20	96	89	77	69	45
Pokkali	96	90	82	60	40
MR 33	91	83	77	59	32
MR68	94	84	77	52	11
MR 84	95	86	78	54	37
MR 52	97	95	87	73	55
MR 211	97	96	88	84	61
MR 219	96	91	78	54	16
MR 220	94	66	59	40	11
MR 232	96	91	87	74	63
BR 29	92	67	51	38	19
BR 40	96	91	83	76	43
Anbar	100	90	24	-	-
LD	98	78	25	-	-
Hamar	98	76	18	-	-

2003; Hakim et al. 2010). Water imbibition is a pivotal process of seed germination; therefore, the presence of salts in the growing media is bound to decrease the osmotic potential of the medium, hence preventing the entrance of water in the seed and subsequent activation of seed metabolism to initiate the germination process (Shereen et al. 2011). Inhibition of metabolic activities such as degradation and mobilization of proteins to the growing embryo or starch degradation through amylase enzymes, due to increased salinity, have also been reported to delay or reduce seed germination (Kamath et al. 1999; Shereen et al. 2011; Liu et al. 2018). Seed ultrastructure is another factor that is affected by salt stress and could reduce the percent germination due to vesiculation or vacuolation of mitochondria, cisterned or dilated endoplasmic reticulum, invagination of plasmalemma into vacuoles, and chromatin condensation (Kamath et al. 1999).

2.5 Effects of salinity on rice yield and yield components

Several studies have addressed the effect of salinity on rice grain yield and yield components (Table 2) with significant yield decreases occurring when salt stress was applied either at vegetative (Abdullah et al. 2001; Zeng et al. 2001; Hakim et al. 2014; Mohammadi et al. 2014; Gerona et al. 2019; Liu et al. 2019a) or reproductive stage (Khatun and Flowers 2006; Lutts et al. 1995; Sultana et al. 1999; Boriboonkaset et al. 2013; Panda et al. 2016). The number of tillers per plant and number of spikelets per panicle are the most salt-sensitive yield components with tillering being reduced when stress was applied at the seedling stage, while the number of spikelets per panicle was reduced when stress was applied between panicle initiation to the booting stage (Zeng et al. 2001). The reduction of tillers number, the most salt-sensitive yield component under salt-stress conditions, is accompanied by yield reductions (Zeng and Shannon 2000; Rad et al. 2012). In addition, when rice plants were exposed to salt stress for long

period, i.e., 20 days, before panicle initiation onwards, significant reductions were observed (Zeng et al. 2001). However, the number of tillers was also reduced when salt stress was applied as early as 3 weeks after germination, with the reductions being more prominent in *Japonica* compared to *Indica* cultivars (Liu et al. 2019a).

Significant decreases have been observed in panicle dry weight, panicle length, and initiation of panicle under salt stress either at the vegetative or the reproductive stage (Abdullah et al. 2001; Wankhade et al. 2013a; Panda et al. 2016). Usually, the adverse effects of salt stress on rice panicles are more prominent in salt-sensitive rice cultivars (Wankhade et al. 2013a), especially when they are exposed to salt stress at the vegetative stage (Mohammadi et al. 2014; Gerona et al. 2019), panicle initiation stage (Saleethong et al. 2013) or at early booting stage (Saleethong et al. 2013; Chunthaburee et al. 2015). However, Gerona et al. (2019) found that salt-tolerant cultivars Pokkali and CSR28 suffered greater panicle length reductions compared to the salt-sensitive RC222 and IR686 whereas the greater panicle length reduction was recorded at cultivar Sadri, a moderately-tolerant cultivar. Spikelet number per panicle is another yield component that is strongly affected by salt stress resulting in significant yield reductions, most notably when plants are exposed to salt stress between the 3-leaf and panicle initiation (Zeng and Shannon 2000) or between the panicle initiation and booting stage (Zeng et al. 2001). In agreement, Panda et al. (2016) reported significant reductions in the number of spikelets per panicle for a *Japonica* cultivar subjected to salt stress at the late booting stage. Decreases in grain weight were reported when rice plants were exposed to salt stress at the seedling stage (Zeng and Shannon 2000; Ndayiragije and Lutts 2007), vegetative stage (Abdullah et al. 2001; Ghorbani Javid et al. 2011; Mohammadi et al. 2014), panicle initiation (Khatun et al. 1995; Saleethong et al. 2013), flowering (Thitisaksakul et al. 2015), or booting stage (Chunthaburee et al. 2015; Boriboonkaset et al. 2013; Panda

Table 2 Effects of salinity on rice yield and yield components. ¹Rice cultivar M-202 was exposed under salinity stress for 5 days after seeding until harvest (based on Zeng, 2000). ²Salinity stress duration on 8-week-old plants until harvest; Averaged across cultivars IKP, AIWU, T67, IR 31785, IR2153, IR 4630, and Panwell (based on Razzaque et al. 2009); ³Salinity stress duration on 75 old plants until harvest at salinity stress

levels (EC) equal of 0, 2, 3, 4, and 5 (based on Lutts et al. 1995). ⁴Average of cultivars IR20, Pokkali, MR33, MR52, MR211, MR219, MR232, and BRRI dhan29. Salinity stress duration on the 5-week-old plant until harvest (based on Hakim et al. 2014). *TGW* thousand-grain weight, the weight, usually in grams, of thousand seeds, and is a measure of seed size

Salinity stress (dS/m)	Tillers (#/plant) ¹	Tillers (#/hill) ²	Primary branch (#/panicle) ¹	Panicle length (cm) ¹	Spikelet (#/panicle) ¹	Spikelet (# panicle) ³	Fertility (%) ¹	TGW ¹	Grain yield (g/plant) ¹	Grain yield (g/hill) ⁴	Harvest Index ¹
0.0	16	20	13	21	176	84	80	4	34	18	0.5
2.0	14	-	13	21	163	60	76	4	30	-	0.5
3.5	13	15	11	18	137	44	74	3	24	-	0.4
4.5	12	-	12	20	132	41	73	3	19	12	0.4
6.0	11	12	11	18	97	36	70	2	12	-	0.4
8.0	10	-	10	18	93	-	52	1	8	6	0.3
11.5	6	5	9	15	54	-	45	1	2	2	0.2

et al. 2016). Losses were increased as NaCl concentrations increased (Zeng and Shannon 2000) with the salt-sensitive genotypes being mostly affected (Khatun et al. 1995; Boriboonkaset et al. 2013; Chunthaburee et al. 2015). Spikelet sterility, due to salt stress, may contribute to decreased rice yields (Zeng and Shannon 2000; Asch and Woopereis 2001; Rad et al. 2012). Additionally, seed set reductions under salt stress have been reported in rice (Rad et al. 2012; Boriboonkaset et al. 2013; Gerona et al. 2019) especially when rice plants are exposed to salt stress at panicle initiation (Zeng et al. 2001; Rad et al. 2012) due to decreases either in pollen viability or stigma receptivity (Khatun and Flowers 2006; Lutts et al. 1995; Abdullah et al. 2001).

Finally, salt stress causes changes in chemical characteristics of grain yield including sugars and starch, protein, amino acids content, and minerals have been reported (Table 3) (Gay et al. 2010; Baxter et al. 2011; Rao et al. 2013; Razzaq et al. 2020).

3 Effects of salinity on rice weeds

The effects of salinity on rice weed biochemistry, physiology, and botanical characteristics along with weed population dynamics will be discussed in the following sections.

3.1 Effects of salinity on rice weeds biochemistry and physiology

Salinity exerts significant effects on weeds' biochemistry, physiology, and growth although the degree of response to salt stress depends on individual species. Chauhan et al. (2013), for example, found that salinity significantly reduced leaf production of *Echinochloa crus-galli* and *E. colona*, but not that of *Trianthema portulacastrum*. In general, weed species perform better than rice under salt-stress conditions (Aslam et al. 1984; Korres et al. 2019) although differential responses have been observed in many circumstances. As

Table 3 Effects of salinity on rice grain quality. Values are averaged across cultivars Illabong, Koshikari, Kyeema, Langi, Millin, and Opus. Under saline conditions, total protein was found lower compared to controls, whereas globulin content was recorded lower under saline conditions compared to control only for Kyeema. On the contrary, albumin was found greater for all cultivars under saline conditions compared to controls for all cultivars tested (based on Baxter et al. 2011)

Treatment	Total protein g/kg flour	Albumin	Globulin
Control	110	7	22
Salinity (2.5 dS m ⁻¹)	91	8	23

mentioned previously, proline holds a significant role in the acclimation to salinity stress by mediating osmotic adjustment (Ashraf and Harris 2004) and increases with increasing salinity levels. Hakim et al. (2014) reported a gradual proline increase for salinity levels up to 24 dS m⁻¹ in all weed species tested (Table 4) with *E. colona* exhibiting the highest proline accumulation followed by *Jussiaea linifolia*, whilst *Leptochloa chinensis* had the least. At 40 dS m⁻¹, the higher proline accumulation was found in *J. linifolia* and the lowest in *Oryza sativa* (Table 4).

The effects of salinity on photosynthesis are dependent on the species and growth stage of weeds. For example, photosynthesis of *Sesbania rostrata*, a member of the Fabaceae family that can be found in rice in the tropics (Reddy et al. 2002), was unaffected when it was exposed to a gradient of NaCl concentrations (Jungklang et al. 2003). However, chlorophyll reductions with increasing levels of salinity, despite the existing variations among weed species (Table 5) (Hakim et al. 2014) will most probably decrease their photosynthetic capacity (Hakim et al. 2021). As shown in Table 5, *Cyperus iria* and *E. crus-galli* showed the lowest decrease in chlorophyll content compared to other weed species, i.e., *E. colona*, *J. linifolia*, *L. chinensis* and *O. sativa*, in that order, when all species exposed at various salinity levels.

However, it is not known if the photosynthetic capacity of these species will be reduced as salinity level increases despite their differences in the photosynthetic pathway i.e. *E. crus-galli* and *C. iria* are C4 species whereas *O. sativa* is a C3 species (Bruhl and Wilson 2007; Korres et al. 2017a). In addition, will possible reductions in photosynthesis of these species reflect reductions in their competitive ability under salt stress conditions?

Both shoot and root mineral contents (i.e., K, Ca, and Mg) decreased as salinity levels increased with weed species exhibiting differential responses regarding salinity level and organ (Table 6). *C. iria* for example showed higher shoot-K content up to 16 dS m⁻¹ but lower than *E. crus-galli* at higher salinity level (Hakim et al. 2014). In addition, *O. sativa*

Table 4 Effect of salinity on proline accumulation as x-fold increase relative to the control (0 dS m⁻¹) in six weed species (based on Hakim et al. 2014)

Species	Salinity level (dS m ⁻¹)					
	4	8	16	24	32	40
	Increase relative to untreated control					
<i>Leptochloa chinensis</i>	1.6	2.4	3.4	4.3	8.1	12.6
<i>Echinochloa crus-galli</i>	2.2	3.0	4.0	6.5	8.0	13.5
<i>Echinochloa colona</i>	2.0	3.4	4.0	7.2	8.0	12.5
<i>Cyperus iria</i>	1.5	2.5	5.3	6.9	11.3	14.4
<i>Oryza sativa</i> L.	1.7	2.7	4.0	5.4	7.7	9.4
<i>Jussiaea linifolia</i>	2.0	3.8	5.4	7.0	10.3	15.6

Table 5 Effect of salinity on total chlorophyll content expressed as % of the control (0 dS m⁻¹) in six weed species (based on Hakim et al. 2014)

Species	Salinity level (dS m ⁻¹)					
	4	8	16	24	32	40
<i>Leptochloa chinensis</i>	93	82	66	54	40	30
<i>Echinochloa crus-galli</i>	99	94	81	67	55	44
<i>Echinochloa colona</i>	96	90	80	71	62	46
<i>Cyperus iria</i>	99	91	83	69	62	50
<i>Oryza sativa</i> L.	86	70	44	36	25	22
<i>Jussiaea linifolia</i>	98	87	74	63	52	41

followed by (fb) *L. chinensis* exhibited the lowest shoot-K content (Hakim et al. 2014). In general, higher shoot- and root-K contents were recorded for *C. iria* and *E. colona* with *O. sativa* showing the lowest value (Fig. 6). Similar trends were recorded for Ca content, which was decreased as salinity levels increased. The high Ca content was recorded in *C. iria* fb, *J. linifolia* fb, *E. crus-galli* fb, *E. colona* fb, *L. chinensis*, and last by *O. sativa* (Fig. 6). The six species with root Ca content were, in descending order, *E. colona* fb, *J. linifolia* fb, *C. iria* fb, *E. crus-galli* fb, *L. chinensis* fb, and *O. sativa* (Hakim et al. 2014). Likewise, the effects of salinity increase on shoot- and root-Mg content followed the same trend as previously mentioned with *C. iria* and *E. colona* or *E. crus-galli* being the less affected weed species and *O. sativa* the most (Hakim et al. 2014) (Fig. 6).

In addition, Wilson and Read (2006), studying the effect of increased salinity levels, reported no significant effects on P and N contents in *E. crus-galli* despite reductions of mineral concentrations at high salinity levels.

3.2 Effects of salinity on weed germination

Salinity usually reduces weed seed germination, although its effect on germination is species-specific (Chauhan and

Table 6 Effect of salinity on Na content in shoots and roots (in parentheses) of six weed species expressed as x-fold increase relative to the control (0 dS m⁻¹) (based on Hakim et al. 2014)

Species	Salinity level (dS m ⁻¹)					
	4	8	16	24	32	40
	Increase relative to untreated control					
<i>Leptochloa chinensis</i>	1 (2)	2 (6)	5 (8)	8 (11)	14 (20)	23 (25)
<i>Echinochloa crus-galli</i>	1 (2)	3 (4)	4 (8)	10 (12)	13 (15)	17 (18)
<i>Echinochloa colona</i>	1 (1)	2 (2)	3 (4)	7 (7)	12 (9)	15 (14)
<i>Cyperus iria</i>	2 (1)	4 (2)	6 (5)	11 (8)	14 (12)	18 (13)
<i>Oryza sativa</i> L.	1 (2)	4 (3)	6 (6)	8 (10)	13 (13)	14 (22)
<i>Jussiaea linifolia</i>	1 (2)	3 (3)	5 (5)	7 (7)	14 (9)	18 (12)

Johnson 2010). Seed germination of *E. colona* was >60% at 5 dS m⁻¹ salinity level while some seeds were able to germinate at 15 dS m⁻¹ salinity level (Chauhan and Johnson 2010). Hakim et al. (2011) recorded decreases in time to 50% germination of ten weed species (Table 7). More specifically, *E. colona* and *C. iria* germinated after 14–16 days of seed exposure at 32 dS m⁻¹ whereas *E. crus-galli*, *C. iria*, *F. miliacea*, *E. colona*, *J. linifolia*, and *O. sativa* germinated after 12–15 days of exposure at 24 dS m⁻¹. All weed species germinated within 5–12 days after seed exposure at 4 and 8 dS m⁻¹ with *C. iria* being less affected at the lowest salinity level (Table 7).

3.3 Salinity effects on weed biological characteristics

Increases in salinity levels resulted in decreases in shoot and root length of *L. chinensis*, *E. colona*, *E. crus-galli*, *F. miliacea*, *S. zeylanica*, *C. iria*, *C. difformis*, *J. linifolia*, *S. grossus*, and *O. sativa* L. (weedy rice) (Hakim et al. 2011). *C. iria*, *E. colona*, and *E. crus-galli* were less affected compared to *J. linifolia*, *L. chinensis* and *O. sativa* L. (weedy rice) which showed a moderate performance up to 24 dS m⁻¹ (Hakim et al. 2011). Germination of *S. grossus*, *F. miliacea*, *C. difformis*, and *S. zeylanica* was most sensitive to salinity with no germination at 16 dS m⁻¹ or higher salinity levels.

In an earlier study, *E. crus-galli*, when exposed to saline conditions approximating 16 dS m⁻¹, showed a 50% reduction in shoot dry weight (Aslam et al. 1984). These authors suggested the ability of *E. crus-galli* to absorb K at high salinity levels selectively as a possible explanation for the high salt tolerance of the species. In addition, Rahman and Ungar (1994) observed a 79% reduction in shoot dry weight when *E. crus-galli* was exposed to approximately 17.5 dS m⁻¹ salinity. These results are in agreement with Wilson and Read (2006) who studied the effects of four mixed-salt salinity solutions (containing Ca, Mg, Na, K, SO₄, and Cl) on the growth of *E. crus-galli* and found reductions in fresh weigh, height, and leaf area across increasing levels of salt-solutions (Table 8). Height of *E. crus-galli* was affected less than dry weight perhaps indicating a competitive advantage of the weed over crops through a shift of resources normally allocated to fresh weight growth toward height increases, as an adaptation to salinity, hence securing the ability of the weed to shade and outcompete rice plants.

3.4 Effects of salinity on weed population dynamics

Weed populations vary considerably in composition and dominance between rice ecosystems mostly due to variations in crop management (Kosaka et al. 2006; Juraimi et al. 2011). Furthermore, weed flora, in saline compared to non-saline environments varies considerably, especially in coastal areas (Hakim et al. 2013). Prevalent weed species in rice fields near

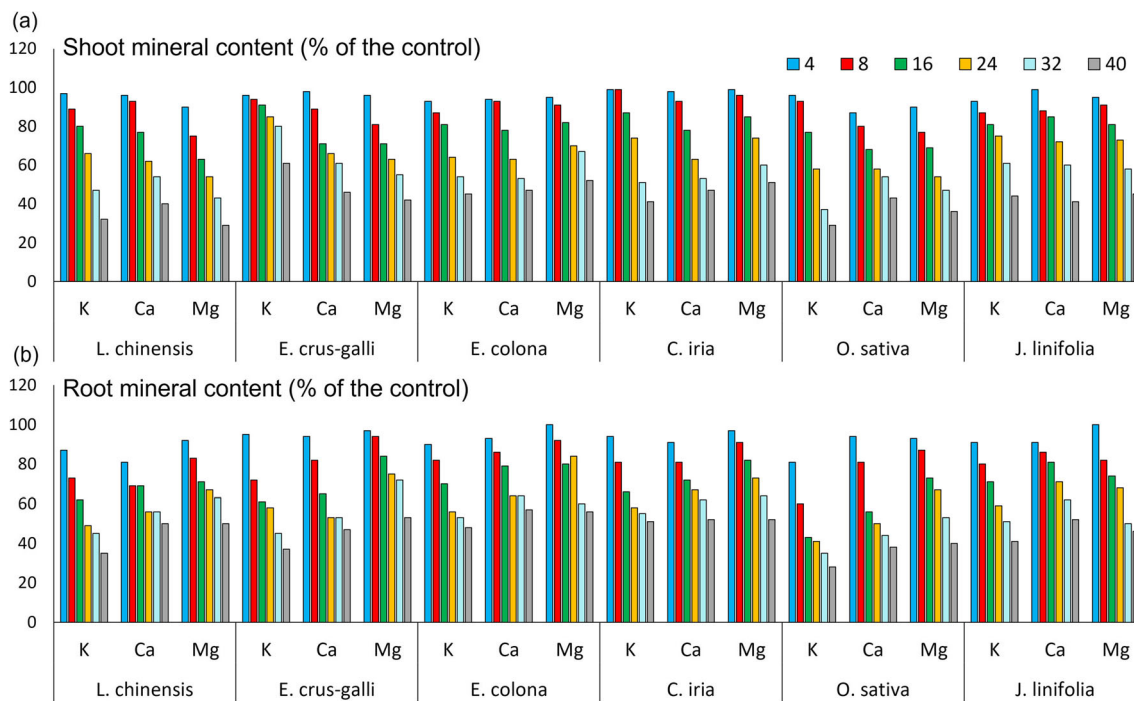


Fig. 6 Effects of salinity level (EC=0, 8, 16, 24, 32, 40 dS m⁻¹) on K, Ca, and Mg content in (a) shoots and (b) roots of six rice weed species. Values are expressed as a percentage of the control (0 dS m⁻¹) (based

on Hakim et al. 2014). EC, electrical conductivity (EC is a measure of the “total salts” concentration in the nutrient solution)

coastal areas in Peninsular Malaysia included species from Cyperaceae, fb Poaceae (47% of the species found) followed by species from Euphorbiaceae, Pontederiaceae, Scrophulariaceae, and Rubiaceae families (Hakim et al. 2013). The most abundant weed species were *E. crus-galli*, *E. colona*, *L. chinensis*, *J. linifolia*, *S. zeylanica*, *Monochoria hastata*, and *Limnocharis flava*. Amongst them, *F. miliaceae*, *C. iria*, *C. difformis*, and *S. grossus* were the most frequent from the Cyperaceae family. In another survey conducted in alternating wet and dry soil conditions or where rice was

transplanted across coastal delta regions in Egypt (salinity of approximately 8 dS m⁻¹ occurs at about 70% in some areas) Turki and Sheded (2002) recorded 71 weed species belonging to 28 families including (in descending order) Poaceae, Compositae, Cyperaraceae, Malvaceae, Lythraceae, Chenopodiaceae, Leguminosae, and Convolvulaceae. The most abundant species were *E. colona*, *E. crus-galli*, *C. difformis*, *Amaranthus viridis*, *Cynodon dactylon*, *Chenopodium murale*, *Ammannia senegalensis*, *Aster squamatus*, *Convolvulus arvensis*, *Cyperus rotundus*, *Ammannia baccifera*, and *C. difformis*. Another survey of 70 rice fields in California, USA, highlighted the abundance of *Sagittaria montevidensis*, *Calycina* ssp., *Ammannia coccinea*, *Bacopa rotundifolia* and taxa from the *Echinochloa* complex (Barrett and Seaman 1980). The most abundant weed species found in rice fields under saline conditions were *Echinochloa* spp., *F. miliaceae*, *Cyperus* spp., and *Ammannia* spp. Most of

Table 7 Effect of salinity (NaCl) on time (days) to 50% germination on different weed species (based on Hakim et al. 2011). - = no germination

Species	Salinity level (dS m ⁻¹)					
	0	4	8	16	24	32
<i>Leptochloa chinensis</i>	3.6	5.4	8.1	10.8	-	-
<i>Echinochloa crus-galli</i>	5.2	8.8	9.5	11.3	13.0	-
<i>Fimbristylis miliacea</i>	8.9	10.1	11.9	13.3	15.2	-
<i>Echinochloa colona</i>	5.8	6.8	8.1	10.0	12.7	14.1
<i>Cyperus iria</i>	3.9	4.8	7.1	10.3	13.1	16.0
<i>Sphenoclea zeylanica</i>	10.1	13.3	15.1	16.2	-	-
<i>Cyperus difformis</i>	6.9	8.4	10.1	12.9	-	-
<i>Oryza sativa</i> L.	6.2	8.1	9.4	10.7	14.9	-
<i>Jussiaea linifolia</i>	5.0	6.6	8.1	10.7	13.4	-
<i>Scirpus grossus</i>	8.6	10.5	11.8	0.0	-	-

Table 8 Effects of salinity on growth of *Echinochloa crus-galli*. Salt solutions contained Ca²⁺, Mg⁺², Na⁺, K⁺, SO₄²⁻ and Cl⁻ (based on Wilson and Read 2006)

Salinity level (dS m ⁻¹)	Fresh weight (g)	Height (cm)	Leaf area (cm ²)
3	2.1	53.4	40.8
7	1.3	46.9	28.8
11	1.4	45.2	31.5
19	0.7	32.8	24.3

the species were able to germinate and survive under relatively high levels of salinity such as *E. crus-galli*, *C. iria*, *E. colona*, *C. difformis* and others. Therefore, the invasiveness and competitive ability of these species under saline conditions could be possibly enhanced. *E. crus-galli* by allocating resources to grow taller could have an advantage over a cultivated crop. These weedy species can easily expand their invasion range by undergoing local adaptation (Parker et al. 2003). Haubensak et al. (2014) concluded that plants grown in saline desert soils display traits that are advantageous in arid environments.

4 Short-term strategies to alleviate the effects of salinity and weed interference on rice crop under salt stress conditions

To alleviate the effects of salt stress on rice several short-term management approaches have been suggested including agronomic, water, and soil management approaches (Hoang et al. 2016) such as the selection of salt-tolerant cultivars, exogenous application of mineral and fertilization management, use of soil amendments, irrigation management and use of salt-tolerant crops in rotation with rice. According to Singh et al. (2016) combining best management practices would enhance the productivity and profitability of rice grown in salt-affected soils. However, these approaches must also enforce pressure on existing weed flora since the additive effects of salinity and weed competition will most probably affect rice grain yield adversely. Nevertheless, the extent to which quantitative and qualitative yield losses occur depends on several factors including weed composition, weed density, and the duration of weed competition (Kwon et al. 1991; Pantone and Baker 1991; Fisher and Ramirez 1993; Rao et al. 2007). Management practices, edaphic characteristics, and regional climate determine the degree of weed impact on the crop (Korres and Froud-Williams 2002). The control of weeds under saline conditions requires the development of integrated weed management programs that facilitate the crop while offering effective weed control.

4.1 Selection of salt-tolerant rice cultivars that can also compete with weeds

The use of salt-tolerant cultivars is a common strategy for salinity management (Dobermann and Fairhurst 2000) since they will secure high seed germination percentage, fast and high crop establishment, high yield production, and eventually weed control. High seed germination percentage under saline environments is a major criterion based on which rice cultivars such as Pokkali, MR 211, MR 232, BR 40, and IR20 (Hakim et al. 2010) are promising candidates. In addition, IR20, MR232, MR211 and BR40 cultivars exhibit a high

speed of germination at high salinity levels (Hakim et al. 2010) along with Basmati 198, Sathra 278, CSR89-IR8, Fakhre Malakand, NSIC RC292 (Salinas 7), Xiushui09, BINA, and Dhan 8 (Sajid et al. 2017). However, some cultivars with high salt-tolerance levels and high germination percentage are tall with low harvest index and increased photosensitivity which is accompanied by low yielding potential compared to the dwarf high-yielding types (Abrol et al. 1988). This is another factor that one should take under consideration when selecting for salt tolerance. According to Platten et al. (2013), early plant vigor is a major salt tolerance trait in rice because the crop can avoid the toxic effects of salinity (Kumar et al. 2013). Several rice genotypes such as IR24, IR36, IR20, IR40, and IR26 display high survival rates attributed to early vigor and fast growth rate when they were exposed to saline conditions (Yeo et al. 1990).

The number of tillers per plant and the number of spikelets per panicle have been reported to be the most salt-sensitive rice yield components with tillering being reduced when the rice plants were exposed to salt stress at the seedling stage (Zeng et al. 2001). Consequently, the selection and use of cultivars that have shown salinity tolerance and early-season growth vigor is another option that merits attention. However, an important question is whether these cultivars are also effective competitors against weeds under salt stress environments. A major component of integrated weed management is the use of more competitive crops (Korres and Froud-Williams 2002). Cultivar traits that confer competitive ability include high seed germination percentage which eventually results in high crop establishment and consequently early ground cover, erect growth habit, tallness, high tillering capacity and leaf area and finally biomass production (Korres 2005, 2018). The germination of *O. sativa* (weedy rice), for example, a weed with early emergence and early population establishment under normal conditions (Olajumoke et al. 2016), was delayed at high salinity levels (Table 7). Therefore, cultivars that have high germination percentage under salt stress conditions such as these mentioned above e.g. IR20, Pokkali, MR52, MR 211, BR29 (Table 1) could also be effective competitors against weeds.

Decreases in shoot growth are more prominent in the salt-sensitive than salt-tolerant rice cultivars and more profound in *Japonica* than *Indica* cultivars such as Nona Bokra and Pokkali (Lee et al. 2003; Ferdose et al. 2009; Liu et al. 2019a). Consequently, the choice of salt-tolerant *Indica* cultivars would benefit shoot growth and also enhance the competitive ability of the crop. However, as mentioned earlier yielding potential of the rice cultivar should be taken into consideration. Rice cultivars such as PR-120, Vandana, RR-151-3 IR88633, Prabhat, Kalinga-III, and IR83927 were found more competitive against associated weeds under saline conditions (Ramesh et al. 2017). Below-ground traits that confer competitive ability include root length density, total root

length, root elongation rate, root spatial distribution, and root volume (Fargione and Tilman 2006; Stevanato et al. 2011; Gealy et al. 2013). Rice cultivars exhibiting these traits will exhibit salt tolerance as well (Kakar et al. 2019). The ability to extract water from deeper layers of the soil profile, under saline conditions where osmotic stress reduces water uptake by roots, may affect or even determine the competitive ability of a cultivar (Song et al. 2010). According to Tu et al. (2014) and Kakar et al. (2019) salt-tolerant genotypes HN2026-4x and Nipponbare-4x, a tetraploid rice cultivar, BR47, and Geumg exhibited better root traits compared to the salt-sensitive genotypes.

4.2 Seed priming

Seed germination and early seedling growth in rice are sensitive to salt stress (Hakim et al. 2010; Afzal et al. 2012) failure which could result in poor crop stand and higher weed infestation, hence lower grain yield. Seed priming through seed hydration and drying aims to enhance the pre-germinative metabolic processes of the seed, thus securing high and rapid germination, seedling growth, and crop establishment (Waqas et al. 2019). Rice seeds, prior to planting, could exogenously be primed with agents such as CaCl_2 , KCl, H_2O_2 (Afzal et al. 2012), proline (Roy et al. 1993; Deivanai et al. 2011; Hua-long et al. 2014), triamine spermidine, gibberellic acid (GA) (Chunthaburee et al. 2014), and trehalose (Abdallah et al. 2016). Primed seeds are usually less affected by salinity during seed germination and emergence than unprinted seeds (Hua-long et al. 2014; Feghhenabia et al. 2020;). According to Jimenez-Arias et al. (2015) and Migahid et al. (2019), seed priming is a practical, cost-effective, and low-risk alternative to improve seed germination and seedling emergence under adverse conditions.

4.3 Transplanting

In cropping systems where rice seedlings are grown in a nursery for 20–40 days before transplanting, salinity at the early growth of the crop is usually of less significance compared to direct-seeded rice cropping systems (Abrol et al. 1988). As stated by Reddy et al. (2017), transplanting rice seedlings can alleviate salinity stress at the vegetative stage. However, salinity stress from the flowering stage onward may still be unavoidable (Reddy et al. 2017). Transplanting of rice seedlings should be done when soil salinity is as low as possible, preferably less than 4 dS m^{-1} ; otherwise, transplanting should be withheld for one or two weeks until the salinity level can be decreased by leaching (Pearson and Bernstein 1959). Experiments conducted by the Indian Council of Agricultural Research-Central Soil Salinity Research Institute revealed that transplanting 4 seedlings hill^{-1} at a spacing of $15 \times 20 \text{ cm}$ produced significantly higher rice

yields than other treatments under saline environmental conditions (Singh et al. 2016). There are also some benefits of transplanting rice against weeds. Transplanted rice seedlings are more competitive against emerging weedy rice than direct-seeded rice cultivation (Rao et al. 2007; Kumar and Ladha 2011; Chauhan 2012). The problem of weed infestation can be significantly reduced by transplanting rice seedlings with a mechanized transplanting machine (Olajumoke et al. 2016). Kim et al. (2000) and Azmi and Karim (2008) found a significant 90% decrease in weedy rice infestation after two to three consecutive seasons using transplanters.

4.4 Exogenous application of minerals and the use of fertilizers

Rice plants under saline conditions experience imbalanced nutrition due to poor uptake and translocation of essential minerals such as N, Ca, K, Mg, and Zn with consequent decreases in growth and productivity (Zhen-Hua et al. 2011; Zayed et al. 2013). Application of minerals such as N, P, K, or Zn alone or in the form of fertilizers can be used to alleviate nutrient deficiencies that occur under saline stress conditions (Miah et al. 1992; Wagdi Abdel Hamid et al. 1993; Kibria and Farhad Hoque 2015; Zaki 2016). Low doses of selenium (Se), a non-essential element to higher plants, can be beneficial to various crops including rice under both stressed and non-stressed conditions (Iqbal et al. 2015; Subramanyam et al. 2019) by strengthening stress tolerance mechanisms (Jiang et al. 2017; Elkesh et al. 2019). The application method of minerals is an important factor for improved results against salinity (Dobermann and Fairhurst 2000). The basal application of N, for example, is less efficient compared with the top-dressed N applications under saline conditions (Dobermann and Fairhurst 2000). In addition, Ebrahimi et al. (2012) reported that the best method of K application is when K becomes available to rice plants through the soil in combination with foliar application. The mineral per se is also an important factor to alleviate the effects of salinity on rice crop nutrition. Calcium, for example, is more effective than Mg and it should be applied at higher rates under saline conditions (Zhen-hua et al. 2011) whereas the application of N and Zn is more appropriate for paddy rice cropping system especially in sandy loam soil when saline water is used for irrigation (Singh et al. 2013). Formulation of the mineral holds an important role as in the case of N, which when it was applied as ammonium sulphate or as a 1:1 mixture of ammonium sulphate with urea was more effective compared to N-application as urea in paddy rice (Hussain et al. 2018). Partial application of N at the beginning of tillering allowed rice to retain lower saline ions and improve K/Na ratio therefore growth and yield of paddy rice in salt-stress conditions (Aslam et al. 1992). However, the use of fertilizers and manures to lessen salinity effects must be performed with great caution since fertilizers are soluble salts

and could aggravate rather than alleviate any salinity problems. In addition, high fertilizer-N rates can lead to high competition levels by the weeds (Burgos et al. 2008). However, the use of different N fertilization rates and strategies may enhance the competitive ability of the rice crop and be used to manage weeds effectively (Khan et al. 2012). According to Sweeney et al. (2008), the effects of N fertilization as a means to manage weeds depend on weed species, environmental conditions, and management practices. Burgos et al. (2011) reported that weedy rice accumulates the available fertilizer-N and efficiently transforms it into higher biomass than cultivated rice cultivars. Therefore, N fertilization should be planned in a way to assist rice in overcoming salinity stress and simultaneously enhance its availability to the cultivated rice as in the case of basal application of N, which as mentioned earlier is less efficient for rice crops than top-dressed N applications under saline conditions. The incorporation of other weed management approaches to minimize weed competition such as stale seedbed rice (Rao et al. 2007) or land levelling prior to N fertilization, especially in direct-seeded rice (Jat et al. 2009), could facilitate the success of N fertilization in favor of the crop.

C. iria, *C. difformis*, *F. miliacea*, *L. chinensis*, and *E. prostrata* were reported to be relatively susceptible to the stale seedbed production method due to their low seed dormancy and inability to emerge when they are buried at a depth > 1 cm (Chauhan and Johnson 2010). In addition, Jose et al. (2013) reported the effectiveness of the stale seedbed production system against weedy rice in direct-seeded rice cropping systems.

4.5 Use of soil amendments

Soil amendments either as mixtures (e.g., copper sulphuric acid and/or grounded rice residues such as hulls, straw, and humic acid or gypsum and/or farmyard manure) (Haq et al. 2001; Rady 2012) or organic manures only (e.g. green manures) (Sharma 1997; Siam et al. 2014) have been suggested as an effective way to ameliorate the salinity stress in rice or pave a way for the land reclamation and increase crop yield under salt-stress environments. The beneficial effects of manures and foliar application of proline at the vegetative stage on rice grain and straw yields by mitigating the detrimental effects of salinity stress have been reported by Sharma (1997). Moreover, according to Zayed et al. (2013), the combined application of manure, biofertilizers, and N fertilizer favored yield production under saline conditions. The most common method to replace the excess of exchangeable Na ions in saline soils with Ca is through the application of CaSO₄ (gypsum) or CaCl₂ followed by water ponding. As gypsum, a neutral salt, dissolves in the water, it releases Ca ions which replace Na ions that will gradually leach deeper into the soil profile. The use of Ca carbonate (CaCO₃) (lime) is not

recommended. The reclaimed soil needs to be managed for long time periods to remain saline-free (Abrol et al. 1988). To the best of our knowledge, there are no available data on the effects of soil amendments on rice weeds.

4.6 Irrigation and use of mulches

Irrigation practices can often lead to increased crop yields under saline soil conditions because the soil moisture content, after irrigation, is maximum whereas the salt concentration is minimal, a condition that favors crop growth (Abrol et al. 1988). Irrigation frequency, irrigation method, and the use of mulches between irrigation periods can be proved effective measures against salinity. More frequent irrigations, for example, maintain high soil moisture content while diluting the concentration of salts in the soil solution therefore minimizing the adverse effects of salts in the soil (Abrol et al. 1988). In addition, frequent irrigation with small quantities of water such as sprinkler irrigation can maintain available soil water under saline conditions (Abrol et al. 1988). Leaching of soluble salts is also accomplished more efficiently when the water application rate is lower than the infiltration capacity of the soil, a condition that is cannot be achieved by flood irrigation methods (Abrol et al. 1988). During periods of high evapotranspiration, there is a tendency for the leached salts to return to the soil surface especially when the soil table is shallow. Therefore, practices that decrease evaporation from the soil surface and/or encourage downward flux of soil water will contribute to controlling the salinity levels near the root zone. To that aid, the use of mulches such as straw mulch on fallow results in greater salt removal through increased leaching efficiency compared to the bare soil flooding or sprinkling (Abrol et al. 1988). The use of mulches is an effective way to suppress weeds mechanically (Korres 2005). Despite the benefits of alternate irrigation methods, flooding is an effective short-term mitigation option against salinity (Abrol et al. 1988) but also a very effective method against rice weeds under saline conditions such as *T. portulacastrum* L. and *C. dactylon* (Jabran and Chauhan 2015). These authors reported the presence of these species in aerobic (non-flooded) but not in anaerobic (flooded) rice. Flooding to 10–20 cm water depth, when rice is at the seedling stage, reduced the infestation of *E. crus-galli* (Dobermann and Fairhurst 2000) and *Cyperus* spp. (Haden et al. 2007). However, the control of weedy rice when it emerges simultaneously with cultivated rice is difficult to control by flooding (Chauhan 2013). As reported by Azmi and Karim (2008) and Olajumoke et al. (2016) the depth, timing, and duration of flooding along with the rice cropping system and crop establishment determine the dominance hierarchy of weeds and the extent of weed suppression. Soil moisture level, which affects the intensity of the salinity stress, and to certain extent weed suppression, varies between water-saving tactics (i.e., permanently aerobic,

alternate wetting and drying, continuously saturated soil) in rice cropping systems (Korres et al. 2017). It is worth mentioning that the wet seeding rice cropping system in seven consecutive seasons allowed certain weed species, mostly *Echinochloa* and weedy rice, to become dominant (Azmi and Karim 2008). Comparative autecological studies on seed biology, plant development, and growth in relation to water management including flooding will provide insightful knowledge in understanding the process involved in the selective nature of water for the survival of weed species (Olajumoke et al. 2016).

4.7 Chemical weed control

Herbicide weed control is the common approach for weed management in cropping systems worldwide. However, there is a great need for proper herbicide selection and determination of effective application rates to control salt-tolerant weeds under saline conditions (Hakim et al. 2021) due to differences in weed population dynamics and composition between saline and non-saline environments (Juraimi et al. 2012). However, the use of herbicides, augmented with other weed management approaches such as hand weeding, has resulted in effective weed control. For example, the use of pretilachlor followed by hand weeding followed by propanil + thiobencarb followed by hand weeding or bensulfuron + MCPA was effective against *E. colona*, *C. iria*, and *J. linifolia* under various salinity levels (Hakim et al. 2015). Research is needed to investigate the potential of integrated weed management methods under saline conditions such as stale seedbed. Pretilachlor, for example, when it was applied before or immediately after shallow tillage and under standing water conditions (2–4 days before draining) offered effective control of weedy rice. Consequently, broadcast planting of pre-germinated seeds of cultivated rice was permitted (Olajumoke et al. 2016). Herbicides, such as oxadiazon and metolachlor, if applied 15 days before rice planting, to avoid phytotoxic effects on rice, can offer effective control of weedy rice (Estorninos Jr et al. 2005) although, even selective herbicides such as oxadiazon, pendimethalin, and oxyfluorfen can trigger the production of reactive oxygen species and cause oxidative stress in rice plants (Langaro et al. 2017). In any case, caution is needed because herbicides respond differently under saline conditions; hence, the optimization of herbicide application rate could potentially prevent possible phytotoxicity injury to rice plants (Hakim et al. 2021). In addition, the production system *per se* can also affect herbicide efficacy. In the absence of standing water, for example, herbicide efficacy was reduced (Allard et al. 2005). The introduction of Clearfield® technology, i.e., an ALS (acetolactate synthase) inhibitor-resistant rice, has provided an effective alternative against weeds, particularly weedy rice (Scarabel et al. 2012; Sudianto et al. 2013). Nevertheless, the evolution of ALS-

herbicide resistance in rice weeds has been recorded in many parts of the world (Heap 2021). Fogliatto et al. (2019) reported a differential response in germination between non-Clearfield and Clearfield rice (i.e., Baldo and CL80, respectively), but also between weedy biotypes that were sensitive and resistant to imazamox herbicide when they were allowed to grow under various salinity regimes (i.e., 0, 5, 10, 15, 20, 25, 30, 35, and 40 mS m⁻¹). They stated that hormesis, which was more profound in Clearfield and resistant weedy rice compared to sensitive *Oryza sativa* biotypes, could be responsible for the stimulation in the germination of resistant biotypes even at moderate salinity levels.

4.8 Miscellaneous tactics against salinity and weeds

4.8.1 Double-rice cropping system

Double-rice cropping system, where suitable conditions exist, has been proposed as a short-term management practice against salinity. Land reclamation during the initial stages of the development of saline soil conditions using rice, over other salt-tolerant crops, is desirable because rice is adapted to grow in flooded conditions that may have a harmful effect on other crops (Abrol et al. 1988). The double-rice cropping system involves the maintenance of standing water for almost the entire growing period which may significantly reduce the salt concentration in the rice root zone by leaching and diluting the soluble salts. To the best of our knowledge, no available data exist on the effects of the double-rice cropping system on weeds and weed infestation under saline conditions.

4.8.2 Scraping soil surface, pre-irrigation, hand weeding

Other management practices against salinity that could possibly facilitate crop competitive ability against weeds through seed germination and crop establishment include scraping and removal of surface soil by mechanical means (Qureshi et al. 2003); pre-planting irrigation to leach salts from the top soil (Goyal et al. 1999a, 1999b); use of ridges or beds for planting in which the seed placement (i.e. shoulders or top of the bed) depends on irrigation design; and planting into pre-flooded field and just after the most of the water has filtered into the soil (Goyal et al. 1999a, 1999b). Hand weeding along with the use of herbicides (Hakim et al. 2015) and/or soil amendments can be used in rice under saline environments as effective weed control. Hand weeding, for example, may increase yield by up to 35% in temporarily flooded lowland rice rather than permanently flooded cropping systems (Latif et al. 2005).

4.8.3 Use of halophytes in rotation

In addition, the use of halophytes, i.e., species that exhibit high salinity tolerance such as *Sarcocornia quinqueflora*,

Tetragonia tetragonioides, *Salicornia europaea*, or legumes, after and/or in rotation with rice, can enhance the removal of excess salts and reduce salinity effects on rice (Dobermann and Fairhurst 2000; Ventura and Sagi 2013).

4.8.4 Fish and rice co-culture

Co-culture of rice with fish is an interesting approach for weed control particularly in estuaries of rivers, streams, ecosystems, or in coastal aquaculture. It has been shown that herbivorous or macrophytophagous and algivorous or microphytophagous fish species can successfully control weeds and weeds-algae in rice (Kutty 1987). Fish species suitable for this purpose in Asia and Africa include *Puntius javanicus*, *Tilapia rendalli*, and *T. zilli*, which are herbivorous, and *T. mossambica*, which are algivorous. Coche (1967) reported that adult *Tilapia rendalli*, stocked at 300 fishes ha⁻¹, maintained an alga- and weed-free environment, 3 weeks after the transplanting of rice seedlings 1 month old. In addition, Mortimer (1957) reported that *T. rendalli*, at the rate of 22 fish kg ha⁻¹, 1 week after rice transplanting, successfully controlled the weeds and algae in rice fields. Increases in organic fertilization by fish excreta and enhanced tillering and reduced activity of harmful insects are the major benefits of the association between rice and fish. On the contrary, extra investment and labor, greater irrigation water supply, and greater water depth that will permit the successful establishment of fish culture, along with extra cost to cover the needs of the fish in food, and the need for rice cultivars tolerant to deep water and low temperature are major the constraints of this approach (Kutty 1987).

4.9 Exogenous application of phytoprotectants

The exogenous application of phytoprotectants has been reported as a means to lessen the negative effects of salinity on rice. The application of vallidomycin A, a trehalose inhibitor, for example, has been reported to increase trehalose content, a disaccharide that plants accumulate in their effort to maintain leaf water potential under salt stress conditions (Abdelgawad et al. 2014). Exogenous application of trehalose (direct or as pre-soaked agent of rice seeds) or proline increased seed weight, rice growth, grain yield, chlorophyll, carotenoid and carbohydrate contents, water use efficiency while inhibited decreases in shoot length, and biomass under salt stress conditions (Lin and Kao 1996; Sobahan et al. 2009; Cha-Um and Kirdmanee 2010; Nounjan and Theerakulpisut 2012; Mostofa et al. 2015; Abdallah et al. 2016). In addition, exogenous application of glycine betaine prevented ultrastructural changes and reductions of thylakoids, mitochondria, PSII efficiency, and protein content under salt stress conditions (Rahman et al. 2002; Demiral and Turkan 2006). The addition of polyamines to a solution used to grow 14-day-old seedlings of a salt-sensitive cultivar until maturity prevented reductions of

biomass under salt-stress conditions (Abdallah et al. 2016). In addition, exogenous application of Pas has been shown to increase seed germination (Habib et al. 2010), anthocyanin and flavonoid content (Ghosh et al. 2012), and photosystem activity (Chattopadhyay et al. 2002). Finally, the exogenous application of phytohormones (i.e., gibberellin, abscisic acid, indoleacetic acid, or kinetin alone or in combination with other compounds) resulted in increases in fresh and dry weight and increases in yield through increases in TWG and improved grain quality through increases of sucrose and glucose content and α -amylase activity (Kim et al. 2006; Li et al. 2010; Gurmani et al. 2011; Javid et al. 2011). However, it will be interesting to investigate the effects of phytoprotectant exogenous application on weeds under field conditions and various salinity scenarios.

4.10 Inoculation with growth-promoting bacteria and endophytes

The use of plant growth-promoting rhizobacteria (PGPR) is an acceptable approach to reducing the effect of stress-induced ethylene on plants (Sajid et al. 2017). Rhizobacteria inhabiting the sites exposed to frequent stress conditions, including salinity, are likely to be more adaptive or tolerant and may serve as plant growth promoters under stressful conditions (Shrivastava and Kumar 2015). Therefore, seed inoculation with PGPR selected from the rhizosphere of rice plants grown in coastal saline soils could stimulate the performance of rice grown under salt stress by lowering the ethylene production and improving the antioxidant potential and the uptake of minerals, chlorophyll content, photosynthesis, germination, and plant growth of rice compared to uninoculated plants (Rangarajan et al. 2003; Sapsirisopa et al. 2009; Bal et al. 2013; Nautiyal et al. 2013; Sen and Chandrasekhar 2015). Rice seeds inoculated with *Pseudomonas* strains or endophytic bacterial (i.e., *Enterobacter aerogenes* and *Enterobacter gergoviae*) strains exhibited improvements in shoot height, root length, dry weight of shoots and roots, grain yield, and 1000-grain weight under salt-stress environments (Ali et al. 2014; Sen and Chandrasekhar 2014). Rhizobacteria used as salt stress remediators in rice include *Pseudomonas pseudoalcaligenes* and *Bacillus pumilus*, and both have increased the concentration of GB (compatible solute) (Jha et al. 2011) or reduced lipid peroxidation and superoxide dismutase activity (Jha and Subramanian 2014). A salt-tolerant endophyte isolated from the salt-tolerant rice cultivar Pokkali, a *Fusarium sp.*, was able to colonize the salt-sensitive rice variety IR-64, promote its growth under salt stress, and confer salinity stress tolerance to its host (Sampangi-Ramaiah et al. 2020). Despite some controversial results, the beneficial effects (Nakbanpote et al. 2014) from the use of PGPR in rice under saline conditions seem like a promising option because it reduces the production cost and the environmental hazards

(Sajid et al. 2017). However, the effects of PGPR on rice weeds are still unknown.

5 Long-term strategies to alleviate salinity effects in rice crops

The development of salt-tolerant cultivars (Miller et al. 2010; Williams and Dickman 2008), altering current land use, and/or modifying existing irrigation practices, soil management, and implementing engineering options to improve irrigation and drainage infrastructure (Shaw et al. 2011) are some long-term salinity mitigation management options. For the purposes of this review, the development of salt-tolerant cultivars and the management of salinity in relation to climate change will be discussed here.

5.1 Genetics of salt tolerance and development of salt-tolerant cultivars

Identification of genes and genetic factors associated with tolerance to soil salinity in rice is of crucial importance. Salt tolerance in rice is polygenic in nature and requires a deep understanding of the genetic basis of salinity tolerance. Genome-wide association (GWA) studies are an effective way to identify candidate genes for salt tolerance in rice. GWA studies could identify potential single nucleotide polymorphisms (SNPs) associated with target traits such as salt tolerance. A GWA study utilizing high-density SNPs conducted by Liu et al. (2019b) identified seven rice accessions (out of 708 rice accessions tested) carrying some previously known and unknown genes (*OsMYB6*, *OsGAMYB*, *OsHKT1;4*, *OsCTR3*, *OsSUT1*, *LOC_Os02g49700*, *LOC_Os03g28300*) associated with high grain yield and related traits (seed setting, panicle number) even under saline stress conditions. The authors also indicated that marker-assisted breeding could be carried out to improve seedling development and yield production under salt-stress conditions by deploying the above-mentioned yield-related salt-tolerance genes. The seven rice accessions (CX315, IRIS313-11,571, IRIS 313-11,584, IRIS 313-11,652, IRIS313-11,698, IRIS 313-9724, and IRIS 313-9725) identified by Liu et al. (2019a) could be used as parents in various rice salt tolerance breeding programs. Another GWA study was recently conducted by Yuan et al. (2020). A total of 21 quantitative trait loci (QTL) were identified and two salt-tolerant candidate genes *OsSTL1* and *OsSTL2* were characterized using 664 cultivated rice varieties from the 3000 Rice Genome Project (3K-RG). Pyramiding such superior genes associated with salt tolerance offers an option for the development of new rice varieties.

Using RNA sequencing approach on reciprocally crossed recombinant progenies between salt-tolerant Horkuch and salt-sensitive IR29 rice cultivars, Razzaque et al. (2019)

identified several up- and down-regulated genes in response to salinity stress in leaf and root tissues. Tolerant rice progenies (F_2) showed upregulation in membrane sensor proteins, Ca signaling pathway enzymes (i.e., trehalose, receptors), and enzymes related to photosynthesis (chlorophyll *a/b* binding). In contrast, the sensitive individuals exhibited upregulation of jasmonate pathway, redox, and apoptosis-related genes. Such studies help blend salt tolerance traits with agronomic performance in rice varieties. Exploiting wild rice germplasm has opened new avenues in breeding rice for salt tolerance (Mishra et al. 2016; Menguer et al. 2017). Recently, the development of rice cultivars tolerant to salinity stress using genes from wild rice has been investigated by Quan et al. (2018). In this study, a salt-tolerant rice line Dongxiang/Ningjing 15 (DJ15) was identified from the cross of salt-tolerant Dongxiang wild rice (*O. rufipogon* Griff.) and cultivated Ningjing16 (NJ16). Furthermore, Quan et al. (2018) characterized nine QTLs for salt tolerance at the seedling stage of rice. In an earlier study, Tian et al. (2011) identified 13 QTLs associated with salt tolerance in wild rice. Evidence of several differentially expressed genes such as *OsHKT1* (a K transporter), *OsHKT7*, and transcription factors such as Zn finger proteins (ZFPs), MYB, and AP2/ERF (APETALA2/ethylene response factor) associated with salt tolerance in wild rice was reported by Zhou et al. (2016).

Mansuri et al. (2020) used an integrative meta-analysis approach to explore various molecular mechanisms contributing to tolerant genotypes responding to salinity stress. Functional annotation of differentially expressed genes located in meta-QTL's suggested involvement in a diverse set of biological functions such as ion transport (*HKT1* (Na/ K transporter), *NCX* (Na/Ca exchanger), *TIP2-1* (aquaporin)), transcription regulation (*TIFY*, *MYB*, *HSF*, *HOX*, *WRKY*, *AP2*, and *GRAS* families), cell wall organization (pectinesterase, Ser/Thr phosphatase, chitinase) and reactive oxygen species (ROS) scavenging during stress response (hydrolase, oxidoreductase, and peroxidase).

5.1.1 Approaches for the development of salt-tolerant rice cultivars

To develop new salt-tolerant rice varieties, various approaches ranging from traditional plant breeding, system biology, and a combination of both are being actively pursued. Traditional plant breeding techniques are socially acceptable, albeit time-consuming, and have retained their value for generating excellent rice varieties tolerant to saline conditions around the world. The use of molecular markers linked to a salt-tolerant trait or the candidate gene to be introgressed is a widely popular plant breeding approach via marker-assisted selection (MAS). Using this approach, salt tolerance QTL *Saltol* was successfully introgressed into rice landraces such as ADT45, CR1009, Gayatri, MTU1010, PR114, Pusa 44, and Sarjoo 52

(Singh et al. 2016a). Rahman et al. (2016), using single nucleotide polymorphism markers and *Saltol* characterization data, identified several rice landraces (Akundi, Ashfal, Capsule, etc.) having significantly lower Na^+/K^+ ratios in their leaves. Using a mutation breeding technique, Deng et al. (2015) were able to isolate a salt-tolerant rice mutant *rst1* showing higher shoot biomass and chlorophyll content.

5.2 Salinity management and climate change

Climate change intensifies the risk of extreme weather incidents and aggravates weather-based disasters (Korres and Dayan 2020). Plausible climate change effects include, amongst others, more frequent fluctuations in precipitation accompanied by extended drought periods (Korres et al. 2016, 2017). Drought stress is a major constraint to rice production, especially in water-limited environments (Mishra et al. 2014). Evenson et al. (1996) reported an average annual global reduction of rice production due to drought of 18Mt. Lowland or flooding (paddy) rice cropping system occupies 31% of the rice-growing area worldwide in contrast to upland or rainfed rice which occupies 11% (Murty and Kondo 2001; Kamoshita et al. 2008). Water and soil salinity will be much more problematic in the near future due to climate change and both will be serious threats to rice cultivation (Velmurugan et al. 2016; Akbari et al. 2020). Irrigation management and water-saving technologies such as alternate wetting and drying irrigation, saturated soil culture, or aerobic rice have been suggested as appropriate climate change mitigation options

(Mitin 2009; Korres et al. 2017) particularly in areas with problems in water availability and extended drought periods. As mentioned earlier, more frequent irrigations, by keeping the soil at a higher soil moisture content, prevent the concentration of salts in the soil solution and tend to minimize the adverse effects of salts in the soil (Abrol et al. 1988). However, the flooded rice system, under saline conditions, is also an effective mitigation option for land reclamation and an effective control method for aggressive rice weeds such as *T. portulacastrum* L. and *Cynodon dactylon* which occur under saline conditions (Jabran and Chauhan 2015). It is important to select management strategies to mitigate salinity effects on rice taking into consideration the control of weeds and also the mitigation of the long-term effects of climate change. More research is needed to quantify the effects of salinity in combination with drought or irregular water availability as a result of climate change on both rice and weeds given that non-flooded rice production systems will most probably favor salt-tolerant weed species.

6 Synthesis and future research

Salt-stress response is affected by several factors such as genotype, severity and extent of stress, type of tissue, and the stage of growth at which the stress occurs (Flowers 2004). Nevertheless, salinity exerts its effects on both rice and weeds. Although the response of rice to salt stress has been investigated in-depth, knowledge about the potential impact of

Table 9 Synthesis and recommendation of short- and long-term management tactics to mitigate salinity and weed competition effects in rice. +=beneficial management tactic; ±=conditional; ND no data available

	Rice management	Weed management	Recommendation/comments
Short-term management tactics against salinity and weeds in rice			
Agronomic			
• Salt-tolerant cultivar	+	+	Recommended
• Transplanting	+	ND	Recommended
• Double rice cropping system	+	ND	Research needed
• Fertilization	+	±	Conditional-Pros and cons
• Soil amendments	+	±	Conditional-Pros and cons
• Irrigation-flooding/mulches	+	±	Conditional-Pros and cons
• Scraping soil surface/use of ridges	+	±	Direct-seeded rice only
Application of phytoprotectants	+	ND	Research needed
Inoculation with growth promoting bacteria	+	ND	Research needed
Seed priming	+	ND	Conditional-Pros and cons
Fish and rice co-cultural systems	Conditional	±	Conditional-Pros and cons
Long-term management tactics against salinity and weeds in rice			
Development of salt-tolerant rice cultivars	+	+	Recommended
Climate change	ND	ND	Research needed

salinity on the weed community is limited. Furthermore, synergistic mitigation options for both salinity and weed control are inadequate. Table 9 serves the purpose of summarizing and suggesting, where suitable, the most important short- and long-term options that could act synergistically and reduce the effects of salinity on the rice crop while managing weeds effectively. The need to develop new rice cultivars that are tolerant to salt stress but also competitive against weeds is a difficult task and research is needed towards that direction. Climate change will exacerbate the effects of salinity on the major rice production regions across the world. We were unable to find literature that presents integrated research that addresses climate change, salinity, and weed management.

The use of salt-tolerant cultivars, rice transplanting systems, and seed priming are all suitable options for both salinity mitigation and effective weed control. Other suggestions listed in Table 9 such as double-rice cropping systems, fertilization management, use of soil amendments, water management, exogenous application of phytoprotectants, or inoculation with growth-promoting bacteria require more research and thorough consideration before their adoption because it is likely that such practices could benefit the crop as well as the weeds. The co-culture of rice and fish, taking into consideration the advantages and disadvantages of this approach, can be used in certain areas, mainly where the availability of water is not problematic.

Using phenomics, Sexcion et al. (2009) were able to associate multiple phenotypic traits such as vigor, shoot-root biomass, Na^+/K^+ ratios to salinity tolerance in varieties Pokkali, Cheriviroppu, FL478, and IR651. Transcriptomic studies using microarray, Illumina sequencing, and other next-generation platforms have greatly contributed to our understanding of candidate genes for salt tolerance under different biological conditions (Kumari et al. 2009; Zhou et al. 2016). At the proteomic level, the use of two-dimensional gel electrophoresis by Zhang et al. (2009) identified *OsRMC* as a negative regulator of salt tolerance in rice. Several salinity-tolerant metabolic pathways were described using metabolomic approaches. One such metabolomic study by Nam et al. (2015) used nuclear magnetic resonance associated carbohydrate and aliphatic structures with salt tolerance traits in rice. New technologies such as phenomics that involve measuring physical traits in response to genetic makeup using non-invasive fluorescence imaging techniques can be employed to deepen our knowledge of salinity tolerance and rice response.

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