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Understanding the Causes, Effects, and Remediation of Salinity in Irrigated Fields: A Review

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Abstract: To boost agricultural production, irrigation will turn out to be more reliant on inadequately described and virtually unmonitored sources of irrigation water supply. Amplified use of irrigation water has resulted in degradation of water and soil quality in numerous areas. The objective of this review is highlighting the causes, effects, and remediation of salinity in irrigated fields. The study analysed some major ions affecting the quality of irrigation water. Precisely, elements including boron, chloride, and nitrogen are harmful to crops. Consequently, it is imperative to detect their origin and consequences. Likewise, there is a need for understanding how they can be removed from irrigation waters. Continuous water quality analysis using chemical indices such as sodium adsorption ratio, sodium percent, residual sodium carbonate, magnesium hazard and permeability index in irrigation water analysis is recommended. The review also highlights the crop tolerance in saline conditions and tolerance limits of individual crops to salinity. Salinity should be monitored for improved irrigation scheme performance. This has necessitated the application of salinity management techniques in irrigation water.

Keywords: Irrigation Water, Salinity, Irrigation Water Quality Indices, Crop Tolerance.

1. INTRODUCTION

Salinity is becoming an environmental problem in many irrigated fields, especially those in semi-arid environments, where most of the vegetables consumed in the country are cultivated [1-3]. As irrigation water quality and cropping patterns change, salinity may harm crops and reduce yield. Exposure to salt damage varies by crop and soil types. Since irrigation farming relied on groundwater, farmers must understand why and how to measure salts in their farms and how to crop exposure to salts may reduce crop yields. Irrigation water quality from

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shallow groundwater can be determined by the total amounts of salts and the types of salts present in the water.

Therefore, salt is a combination of two elements or ions. One has a positive charge (e.g., Na, Ca, Mg, etc.), and the other has a negative charge (e.g., Cl, NO_3, SO_4, etc.,). Water may contain a variety of salts including sodium chloride (table salt), sodium sulfate, calcium chloride, calcium sulfate (gypsum), magnesium and chloride. The types and amounts of salts in water, and thus the salinity of that water, largely depend on the source of solutes [4-6]. The quality of irrigation water also depends on the composition of the underlying aquifer rock formations from which the water is driven [7-10]. When these are coastal (ocean) aquifers, generally they will have higher salt levels and produce water that is brinier.

However, the quality of surface water depends mainly on the source of runoff. Drainage water from irrigated fields, saline seeps, oil fields, municipal and industrial wastewaters generally has higher salt levels [11-13]. Table 1 shows different units of measurement for total soluble salts which represent the same critical value to significant crops. High salts concentrations in irrigation water can cause two major problems in crop production: *salinity hazard* and *sodium* hazard [14, 15]. When irrigation water is used by plants or evaporates from the soil surface, salts contained in the water are left behind and can accumulate in the soil. These salts generate a salinity hazard because they compete with plants for water. Even if a saline soil is a water-saturated, plant roots may be unable to absorb the water, and plants will show signs of drought stress. Foliar applications of salty water often cause marginal leaf-burn and, in severe cases, can lead to defoliation and a significant reduction in crop yields. When the sodium level in the soil becomes high, the soil will lose its structure and become dense and form hard layers on the surface [16, 17]. Understanding measures of irrigation water quality is necessary for improved irrigated agriculture. Irrigated agriculture is facing rising competition worldwide for access to reliable, low cost, high-quality water [18, 19]. This paper highlights some measures of irrigation water quality.

Table 1. Critical values for salts in irrigation water for significant crops

Total Dissolved Salts (Electrical Conductivity or Total Dissolved Solids*)	**Peanuts**	**Corn**	**Grain sorghum**	**Cotton**
Micromhos per centimeter (umhos.cm)	2100	1100	1700	5100
Microsiemens per centimeter (uS/cm)	2100	1100	1700	5100
Millimhos per meter (mmhos/cm)	2.1	1.1	1.7	5.1
Decisiemens per meter (dS/m)	2.1	1.1	1.7	5.1
Parts per million (ppm)	1344	704	1088	3264
Milligrams per liter (mg/L)	1344	704	1088	3264
Sodium Adsorption Ratio (SAR)				
No Units, just number	10	10	10	10
Toxic Ions (Resulting in Foliar Injury)				
Boron				
Parts per million (ppm)	0.75	2.0	3.0	3.0
Milligrams per liter (mg/l)	0.075	2.0	3.0	3.0
Milliequivalents per liter (meq/l)	0.075	0.2	0.3	0.3
Chloride				
Parts per million (ppm)	400-500	533	710	710

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Milligrams per liter (mg/l)	400-500	533	710	710
Milliequivalents per liter (meq/l)	17-21	23	31	31
Sodium				
Parts per million (ppm)	400-500	533	710	710
Milligrams per liter (mg/l)	400-500	533	710	710
Milliequivalents per liter (meq/l)	17-21	23	31	31

Universally, irrigation is the greatest consumptive use of freshwater [20, 21]. As the earth's population expands, the risk raises that more people will be denied of sufficient food deliveries in destitute areas, especially those subject to water scarcity. Agricultural production of food needs to improve by a projected 60% by 2050 to guarantee global food security and irrigation will progressively be called upon to assist meet this demand [20]. In the race to improve agricultural productivity, irrigation will grow to be even more reliant on substandard sources of water. So, it is of paramount importance to gain access to our current state of knowledge and investigate the impacts of irrigation water quality on crops. This understanding will help guarantee adequate crop production to meet expanded demand as well as to sustain proper food and soil quality.

1.1. Salinity, Soil Permeability, Toxicity, pH and Alkalinity

Permeability problem associated with water quality occurs when the rate of water infiltration into and through the soil is reduced by the effect of specific salts or lack of salts in the water to such an extent that the crop is not adequately supplied with water and yield is reduced [22-24]. The low soil permeability makes it very difficult to provide the crop with water. It may significantly add to cropping complications through crusting of seedbeds, waterlogging of surface soil and associated crop disease, weed, oxygen and nutritional complications. Soil permeability is assessed initially, from total salts in the water since low salt water can cause poor soil permeability due to the incredible capacity of pure water to dissolve and remove calcium and other soluble elements in the soil [22, 25-27]. This from a comparison of the relative content of sodium to calcium and magnesium in the irrigation water.

Moreover, carbonates and bicarbonates ions affect soil permeability and need to be assessed. The adverse influence of sodium on soil permeability has been documented for many years [28-33]. Nonetheless, in many cases, the assessment of the sodium influence alone has proven to be in error essentially because the interaction of three factors determines a water's long-term impact on soil permeability [22]. These factors are:

i. Sodium content relative to calcium and magnesium;
ii. Bicarbonate and carbonate content; and
iii. The total salt concentration of the water.

A concurrent analysis of these has been applied to soils in ancient times and later in the 1970s has been applied to estimating the permeability hazard of irrigation waters to soils. These are widely used nowadays for measuring irrigation water quality. Toxicity in irrigation water can be caused when some aspects in the water are taken up by the crop and accumulate in amounts that result in reduced crop yield [23, 34-36]. This is usually related to one or more specific ions in the water viz. boron, chloride, and sodium [22]. Many other problems related to irrigation water quality occur with an adequate incidence that they should be explicitly noted. These comprise of excessive vegetative growth, lodging and delayed crop maturity consequential from excessive nitrogen in the water supply, white coatings on fruit or leaves

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due to sprinkler irrigation with bicarbonate-rich water and suspected abnormalities indicated by an unusual level of pH in the water [22].

The acidity or basicity of irrigation water is expressed as pH (< 7.0 acidic; > 7.0 basic)—the average pH for irrigation water ranges from 6.5 to 8.4. Unusually low pH levels are not typical in irrigation waters but may cause accelerated irrigation system corrosion where they occur [37]. High pH concentrations above 8.5 are often caused by elevated bicarbonate (HCO_3) and carbonate (CO_3) ions, known as alkalinity. High carbonates cause Ca and Mg ions to form insoluble minerals leaving sodium as the overriding ion in solution [38-40]. This alkaline water could increase the impact of high SAR water on sodic soil environments. Extreme bicarbonate concentrates can also be problematic for drip or micro-spray irrigation systems when calcite or scale build-up causes abridged flow rates through cavities or emitters. In these situations, an amendment by injecting sulfuric or other acidic materials into the system may be required [37].

Irrigation water quality and drainage problems are regularly interconnected, and adequate control of a possibly damaging water table is documented as an indispensable obligation to thriving long-term irrigated agriculture [22, 41-43]. Salts will accrue on top of a water table. Suppose water tables are very shallow (e.g. 2 meters below ground). In that case, they can become an essential causal source of additional salts in the crop root zone. When unrestrained in shallow water tables, salinity problems can occur, even where irrigation water quality is good, especially in arid and semi-arid environments. With high water tables of low quality, salts can be expected to accrue quickly in the crop root zone. In contrast, with good quality groundwater, they will still accrue but at a much slower rate.

2.0.Irrigation water quality in groundwater-fed irrigation fields

The suitability of irrigation water, from a quality perspective, is determined by its possible to cause problems and is connected to the unique management practice required or the yield decrease caused [23, 44-46]. In most cases is at the farm level, the evaluation must be done in terms of the specific use and potential hazard to crop production under the existing management capability and farm conditions [22]. In the assessment of irrigation water quality, a water sample should be analysed for three significant factors:

i. Total soluble salts;
ii. Sodium hazard (SAR);
iii. Toxic ions; and
iv. Permeability.

Total soluble salts measure the salinity hazard by estimating the combined effects of all the different salts that may be available in the water [47-49]. It is calculated as the electrical conductivity (EC) of the water. Salty water conveys an electrical current better than pure water, and EC rises as the number of salt increases [22]. Many people make the mistake of testing only for chlorides, but chlorides are just one part of the salts. They do not determine the entire salinity in irrigation waters. Sodium hazard is based on a calculation of the SAR. This measurement shows if sodium levels are high enough to damage the soil or if the concentration is excellent sufficient to reduce plant growth [50-52]. Occasionally a factor called the exchangeable sodium percentage (ESP) may be listed or debated on a water test; though, this is essentially a measurement of soil salinity, not water quality [22, 36, 53, 54]. Toxic ions include elements like chloride, sulfate, sodium, and boron. Occasionally, even though the salt level is not extreme, one or more of these elements may become toxic to plants. Many plants

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are particularly sensitive to boron. In general, it is best to request a water quality analysis that lists the concentrations of all major cations (Ca, Mg, Na and K) and anions (Cl, SO_4, NO_3, B) so that the levels of all elements can be evaluated and compared with the established standard.

2.1. Total dissolved solids

Increased salts concentrations in irrigation water make it very difficult for plants to extract water from the soil [2, 55, 56]. Experiments have shown that under the osmotic pressure of 15 – 20 atm, plants wilt permanently. The relationship between osmotic pressure and concentration of a solution is defined thus;

$$p = iRTC \quad (1)$$

where *P* = osmotic pressure, atm; *i* = Vonthoff factor; *R* = gas constant, litre-atm; *T* = absolute temperature and *C* = concentration, moles/l. In very weak solution *i* may be identified with the number of ions per molecules . For instance, in 0.1% NaCl, *i* = 2, C = 1mg/l = 1/58.5 moles/l. Note, the atomic weight of Na + Cl ions =58.8; taking RT = 22.4 litre-atm,

$$P = \frac{2 \, x \, 22.4}{58.5} = 0.766 \, atm \quad (2)$$

In 0.1% Na_2SO_4, *i* = 3, $P = \frac{3 \, x \, 22.4}{142} = 0.470 \, atm$ (3)

In 0.1% $CaCl_2$, *i* = 3, $P = \frac{3 \, x \, 22.4}{111} = 0.605 \, atm$ (4)

In 0.1 $CaSO_4$ *i* = 2, $P = \frac{2 \, x \, 22.4}{136} = 0.329 \, atm$ (5)

Therefore, the chlorides are more toxic than sulfates. However, the toxicity as a result of a given salt concentration rises with increased temperature.

2.2. Relative proportions of sodium to other cations

Although higher salinity in irrigation water causes the development of saline soil, at the same time, high sodium levels in irrigation water cause the formation of an alkali soil [57, 58]. The USDA defined an alkali soil as having a pH of 8.5 and above with a Na-saturation of 15% and above. An alkali soil tends to have an unfavourable structure, puddles easily and limits the aeration. Also, elevated Na-saturation directly causes Ca deficiency. Irrigation water having a low sodium adsorption ratio (SAR) is therefore required.

2.2.1. Sodium adsorption ratio

Sodium adsorption ratio (SAR) is used to measure alkali and sodium hazard to crops. Table 2 shows the classification of sodium hazard of irrigation water based on SAR [59-61]. Sodium adsorption ratio is defined thus:

$$SAR = Na^{+} / \sqrt{[Ca^{2+} + Mg^{2+})} \, / \, 2] \quad (6)$$

Table 2. Sodium hazard of irrigation water based on SAR Values.

SAR	Sodium hazard	Remarks
>10	Low	Use on Na sensitive crops (e.g. Avocados) must be cautioned
10-18	Medium	Amendments (e.g. Gypsum) and leaching required
18-26	High	Generally unsuitable for continuous use
>26	Very high	Mostly unsuitable for use

After Fipps [62].

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Figure 1 shows the classification of irrigation water base on sodium and salinity hazards to crops, in southwestern Sokoto Basin. Most of the groundwater samples (97.5%), fall in low sodium-low EC class, suggesting groundwater of low sodium and low salinity. This water type has no danger of exchangeable sodium. About 2.5% of groundwater samples fall in high salinity-medium sodium water type. Under favourable drainage conditions, this water type can be used to irrigate salt-tolerant and semi-salt tolerant crops. However, irrigation water with low salinity and low SAR can lead to problems relating to water permeability. Evaluation of the permeability index is therefore necessary [60]. Low salinity irrigation waters are corrosive and tend to reduce surface soils of readily soluble minerals and salts. They have a strong tendency to dissolve all sources of calcium from the surface soil rapidly causing the finer soil particles to disperse, to fill pore spaces and to seal the soil surface [55, 63-65]. Very low salinity waters (EC <0.2 µS/cm) often result in soil permeability problems and the lower the EC in waters, the greater the potential of a permeability problem [22].

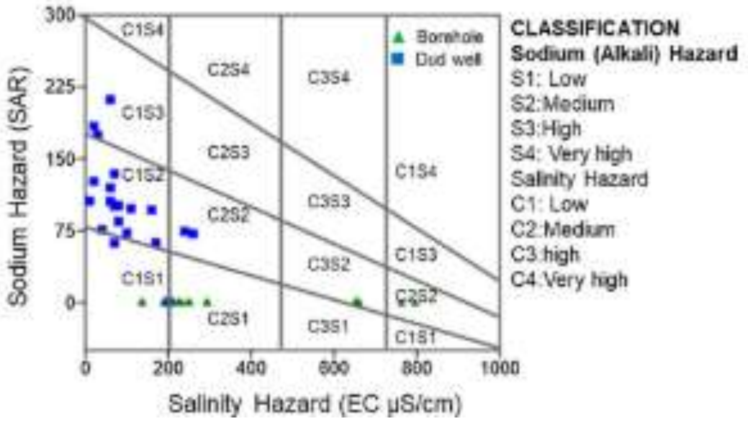

Figure 1. Irrigation water classification Using USDA Diagram. After Wali, et al. [60].

2.2.2. Sodium Percent

Sodium reacts with soil to decrease soil permeability. Elevated sodium levels cause cation exchange between Mg and Ca from the soil, which eventually reduces water and air circulation under wet conditions [66-68]. Sodium percent is defined thus:

$$Na^{+}(\%) = [(Na^{+})x100/(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})] \quad (2)$$

Wilcox diagram is used to classify irrigation water based on sodium percent. Figure 2 shows that sodium percent in groundwater is less than 20, in Southwestern Sokoto Basin. This especially required for irrigation use. Based on this classification, 80% of groundwater samples fall in good-excellent class, 10% suitable, 5% doubtful to unsuitable, and 5% unfit [60]. Table 3 presents a guideline for interpretation of irrigation water quality.

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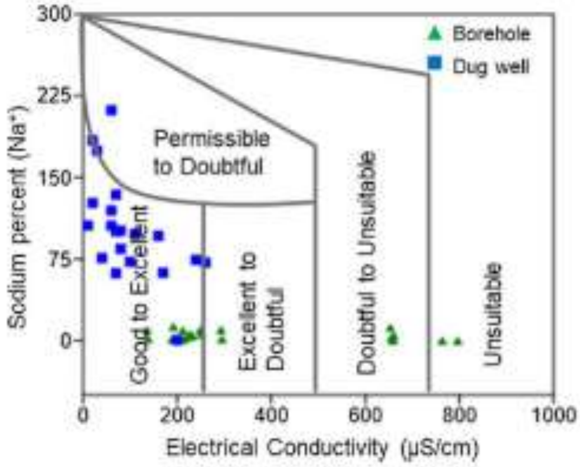

Figure 2. Wilcox plot of groundwater classification. After Wali, et al. [60].

Low sodium in irrigation water is attributable to the ion exchange reaction between Ca and Na, perhaps caused by residence time and sluggish sub-surface flows. High sodium in irrigation water can result in a severe soil permeability problem [59-61]. Meeting the crop water demand under these conditions may become extremely difficult. Besides, other issues such as crop germination, soil aeration, disease and weed control due to surface water ponding and stagnation may arise, needing special attention. Table 4a-c shows yield decrement expected for certain crops due to the salinity of irrigation water when standard surface irrigation methods are used.

Table 3. Guidelines for interpretation of irrigation water quality.

Irrigation Problem	**Degree of Problems**		
	No Problem	**Increasing Problem**	**Severe Problem**
SALINITY (affects crop water availability)			
EC [µS/cm]	<0.75	0.75 – 3.0	>3.0
PERMEABILITY (affects infiltration rate into the soil)			
EC [µS/cm], SAR[1&2] Montrimorillonite (2:1 crystal lattice) Illite-Vermicule (2:1 crystal lattice) Koalinite-sesquioxides (1:1 crystal lattice)	>0.5 <6 <8 <16	0.5-0.0.2 6-9[3] 8-16[3] 16-24[3]	<0.2 >9 >16 >24
SPECIFIC ION TOXICITY (affects sensitive crops)			
Sodium[4&5](adj. SAR) Chloride[4&5] (meq/l) Boron (mg/l)	<3 <4 <0.75	3-9 4-10 0.75-2.0	>9 >10 >2.0
MISCELLANEOUS EFFECTS (affects susceptible crops)			
NO_3 – N (or) NH_4 – N(mg/l) HCO_3 (meq/l) overhead sprinkling)	<5 <1.5	5-30 1.5-8.5	>30 >8.5
pH	[Normal Range 6.5-8.4]		

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Note: [1]adj. SAR = adjustable Sodium Adsorption Ratio; [2]Values presented are the dominant type of clay mineral in the soil since structural stability varies between the various clay type. Problem is more likely to develop if water salinity is low; [3]Use the lower range of EC <0.4 µS/cm; Use the intermediate-range if EC =0.4 -1.6 µS/cm; and Use upper limit if EC >1.6 µS/cm; [4]Most tree crops and woody ornamentals are sensitive to Na and Cl (use values are shown). Most annual crops are not sensitive (use salinity tolerable Table 2); and [5]With sprinkler irrigation on sensitive crops, Na or Cl above 3 meq/l under certain conditions has resulted in excessive leaf absorptions and crop damage. After Ayers and Westcot [22].

Table 4. (a)Variability of crop tolerance to salinity in irrigation water.

Crop	**0%**		**10%**		**25%**		**50%**		**Max**
	EC_a[1]	EC_b[2]	EC_a	EC_b	EC_a	EC_b	EC_a	EC_b	EC_a[3]
Almond	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.7	7
Apple pear	1.7	1.0	2.3	1.6	3.3	2.2	4.8	3.2	8
Apricot	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	6
Avocado	1.3	0.9	1.8	1.2	2.5	1.7	3.7	2.4	6
Beans	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.5
Berley	8.0	5.3	10	6.7	13	8.7	18	12	28
Blackberry	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.8	7
Boysenberry	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.8	7
Broadbean	1.6	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12
Corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Cotton	7.7.	5.1	9.6	6.4	13	8.4	17	12	27
Cowpea	1.3	0.9	2.0	1.3	3.1	2.1	4.9	3.2	8.5
Date palm	4.0	2.7	6.8	4.5	10.9	7.3	17.9	12	32
Fig	2.7	1.8	3.8	2.6	5.5	3.7	8.4	5.6	14
Flax	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Grape fruit	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8
Groundnut	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.5
Lemon	1.7	1.1	2.3	1.6	3.2	2.2	4.8	3.2	8
Orange	1.7	1.1	2.3	1.6	3.2	2.2	4.8	3.2	8
Peach	1.7	1.1	2.2	1.4	2.9	1.9	4.1	2.7	6.5
Plum	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.8	7
Raspberry	1.0	0.7	1.4	1.0	2.1	1.4	3.2	2.1	5.5
Rice	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11.5
Sesbania	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	16.5
Sorghum	4.0	2.7	5.1	3.4	7.2	4.8	11	7.2	18
Soybean	5.0	3.3	5.5	3.7	6.2	4.2	7.5	5.0	10
Strawberry	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4
Sugar beet	7.0	4.7	8.7	5.8	11	7.5	15	10	24
Sunflower	5.3	3.5	6.2	4.1	7.6	5.0	9.9	6.6	14.5
Walnut	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8
Wheat	6.0	4.0	7.4	4.9	9.5	6.4	13	8.7	20

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Table 4. (b) Variability of vegetable crops tolerance to salinity in irrigation water.

Beans	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.5
Beets	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15
Broccoli	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	13.5
Cabbage	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12
Cantaloupe	2.2	1.5	3.6	2.4	5.7	3.8	9.1	6.1	16
Carrot	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.1	8
Cucumber	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10
Lettuce	1.3	0.9	2.1	1.4	3.2	2.1	5.2	3.4	9
Onion	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.5
Pepper	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	8.5
Potato	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Radish	1.2	0.8	2.0	1.3	3.1	2.1	5.2	3.4	9
Spinach	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15
Sweet corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Sweet potato	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	10.5
Tomato	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	12.5

In using crop tolerance data, it must be recognised that actual production with water of the quality indicated can range from the full 100% potential down to zero, depending upon any one of several factors other than water quality. The values given in Table 4 represent the maximum production potential for the quality of irrigation water under optimum environmental conditions of use. The amounts recommended as tolerance limits to the salinity of applied water (EC_b) may seem high at first instance. But, comparing these recommended values with field trials using comparatively poor-quality irrigation waters, as reported for example from arid and semi-arid environments, appears to be reasonably good agreement on salinity tolerance of crops tested [22].

Table 4. (c). Variability of Forage crops tolerance to salinity in irrigation water.

Alfalfa	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	15.5
Barley (hay)	6.0	4.0	7.4	4.9	9.5	6.3	13.0	8.7	20
Bermuda grass	6.9	4.6	8.5	5.7	10.8	7.2	14.7	9.8	22.5
Clover, berseem	1.5	1.0	3.2	2.1	5.9	3.9	10.3	6.8	19
Corn (forage)	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15.5
Crested wheat grass	3.5	2.3	6.0	4.0	9.8	6.5	16	11	28.5
Harding grass	4.6	3.1	5.9	3.9	7.9	5.3	11.1	7.4	18
Lovegrass	2.0	1.3	3.2	2.1	5.0	3.3	8.0	5.3	14
Orchard grass	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	17.5
Perennial rye grass	5.6	3.7	6.9	4.6	8.9	5.9	12.2	8.1	19
Sudan grass	2.8	1.9	5.1	3.4	8.6	5.7	14.4	9.6	26
Tall fescue	3.9	2.6	5.8	3.9	8.6	5.7	13.3	8.9	23
Tall wheat grass	7.5	5.0	9.9	6.6	13.3	9.0	19.4	13	31.5
Trefoil, big	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	7.5

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Trefoil, birdsfoot narrow leaf	5.0	3.3	6.0	4.0	7.5	5.0	10	6.7	15
Vetch	3.0	2.0	3.9	2.6	5.3	3.5	7.6	5.0	12
Wheat grass	7.5	5.0	9.0	6.0	11	7.4	15	9.8	22
Wildrye beardless	2.7	1.8	4.4	2.9	6.9	4.6	11.0	7.4	19.5
Meadow foxtail	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12
Clover, alsike, ladino, red, strawberry	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	10

Note: EC_a^1 = electrical conductivity of the saturation extract of the soil reported in millimhos per centimetre at 25°C; EC_b^2 means electrical conductivity of the irrigation water in millimhos per centimetre at 25oc. This assumes about a 15-20% leaching fraction and an average salinity of soil water taken up by crop about three times that of the irrigation water applied; and EC_a^3 = the maximum electrical conductivity of the soil saturation extract that can develop due to the listed crop withdrawing soil water to meet its evapotranspiration demand. At this salinity, crop growth ceases (100% yield decrement) due to the osmotic effect and reduction in crop water availability to zero. After Ayers and Westcot [22].

Crop tolerance is presented in the tables as if tolerance was a fixed value. This is not precisely so. Crop tolerance does change with water management practices as well as with stage of growth, rootstocks, diversities and the climate [69-71]. For many crops, the germinating and early seedling stage is the most sensitive - sugar beets, rice, wheat, barley and several vegetables - and soil salinity (EC_a) more than 4 µS/cm in the area of the germinating seed, may delay or inhibit germination and early growth. The tolerance values, as presented in Table 4, are based on the response from the late seedling stage [22]. However, climate plays an imperative role in crop tolerance. In general, crops grown in colder climates or during the more freezing time of the year will be more tolerant to adverse salinity than during warmer periods and periods of low humidity or high evapotranspiration rates. Fertilisers usually are not believed to increase salt tolerance of crops. Instead, they may increase yields if fertility is a limiting factor. In some cases, experience has shown that the tolerance limits may be too high. The apparent difference may be as a result of the existence of a high-water table which acts as a primary source of added salinity [22, 72].

In the occurrence of a high-water table, salt distribution in the rooting zone will typically be diverse. Instead of salts increasing with depth, salts will often be highest near the surface, decreasing with depth, as shown in Figure 3 [60]. Under such circumstances, soil salinity may be extreme. The full crop production potential for the quality of water as shown in the tolerance table (Table 4), may not be possible until suitable drainage and water table control are accomplished by artificial drainage (open or covered drains or drainage wells) or by substantial changes in water management [22].

2.2.3. Permeability index

Soil permeability refers to the ease with which water passes in and infiltrates down through the soil and is usually measured and reported as an infiltration rate [22]. Soil permeability is an important parameter which determines the nutritional intake in plants. Continued use of irrigation waters enriched in Na, Ca, and HCO_3 affects soil permeability. Permeability index [73], is defined thus;

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$$Pi = [Na + \sqrt{HCO_3} CO_3 / (Ca + Mg + Na)] \quad (10)$$

Figure 4 shows Doneen's chart of irrigation water classification. Permeability index of water can be classified into three (3) classes: Class III, Class II, and Class I. Irrigation water samples which fall in Class II and I are considered suitable for irrigation purpose. A permeability problem occurs if the irrigation water does not enter the soil quickly enough during irrigation to replenish the soil with water needed by the crop before the next irrigation [22]. A reduced permeability is generally a problem of the upper few centimetres of soil but occasionally may occur at deeper depths. This leads to a reduced water supply to the crop just as a salinity problem does but for a different reason. Permeability decreases the quantity of water to be found in storage. In contrast, salinity decreases the availability of water in storage. An infiltration rate of 2.5 mm/hour is considered low while 12 nuns/hour is relatively high [22].

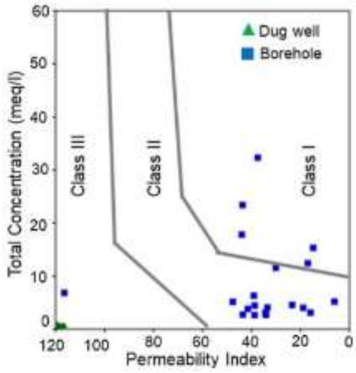

Figure 4. Classification of irrigation water based on permeability index. After Wali, et al. [60].

However, permeability can be affected by numerous factors other than water quality including physical characteristics, such as soil texture, layering or stratification, and compaction, and chemical elements such as the type of clay minerals and exchangeable cations. The guidelines of Table 5 refer to permeability problems as they relate directly to the unfavourable changes in soil chemistry caused by the quality of the irrigation water applied and are related to one of two causes - low salinity or high sodium in the irrigation water. They do not relate to problems of physical soil characteristics such as texture and compaction [22]. If the conditions of use or local experience indicate a different relationship than the 1: 1.5 concentration factor for water salinity to soil salinity (EC_a - 1.5 EC_b), the present values for tolerance to salinity can be changed and new tables prepared. But this should only be assumed if well documented local experiences show the existing tables to be inaccurate. Changes based on a limited number of field trials or observations could prove equally wrong [22].

The soil salinity values (EC_a) for crop tolerance are good values, supported by extensive research in many parts of the world. The relationship of water salinity to soil salinity may vary with management and local conditions applied. By selecting crops and by using good management, a farmer may obtain better yields with the water available or may find that water considered 'unusable' under his initial concept of quality may be 'usable' under certain situations [22]. Low water is often better than no water and, if the water is usable, agriculture may need to find a use for it, rather than discharge it as waste. In situations where wastewater is very toxic, it can be used to water tree plantations, particularly those that are not consumed

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(e.g. pulp). This could serve as bioremediation, since vegetation can absorb the nutrients, thereby reducing their levels in shallow aquifers.

Table 5. Recommended limits for elements in irrigation water.

Constituent	**Long-term use (mg/l)**	**Short-term use (mg/l)**	**Remarks**
Aluminium (Al)	5.0	20	Can cause nonproductivity in acid soils, but soils at pH 5.5 to 8.0 will precipitate the ion and eliminate toxicity.
Arsenic (As)	0.10	2.0	Toxicity to plants varies widely, ranging from 12 mg/L for Sudan grass to less than 0.05 mg/L for rice.
Beryllium (Be)	0.10	0.5	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans.
Boron (B)	0.75	2.0	Essential to plant growth, with optimum yields for many obtained at a few-tenths mg/L in nutrient solutions. Toxic to many sensitive plants (e.g., citrus) at 1 mg/L. Most grasses relatively tolerant at 2.0 to 10 mg/L.
Cadmium (Cd)	0.01	0.05	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/L in the nutrient solution. Conservative limits recommended.
Chromium (Cr)	0.1	1.0	Not generally recognised as essential growth element. Conservative limits recommended due to lack of knowledge on toxicity to plants.
Cobalt (Co)	0.05	5.0	Toxic to tomato plants at 0.1 mg/L in the nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Copper (Cu)	0.2	5.0	Toxic to a number of plants at 0.1 to 1.0 mg/L in nutrient solution.
Fluoride (F)	1.0	15.0	Inactivated by neutral and alkaline soils.
Iron (Fe)	5.0	20.0	Not toxic to plants in aerated soils but can contribute to soil acidification and loss of essential phosphorus and molybdenum.
Lead (Pb)	5.0	10.0	Can inhibit plant cell growth at very high concentrations.
Lithium (Li)	2.5	2.5	Tolerated by most crops at up to 5 mg/L; mobile in soil. Toxic to citrus at low doses recommended limit is 0.075 mg/L.
Manganese (Mg)	0.2	10.0	Toxic to several crops at a few-tenths to a few mg/L in acid soils.
Molybdenum (Mo)	0.01	0.05	Nontoxic to plants at average concentrations in soil and water. Can be toxic to livestock if forage is

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			grown in soils with high levels of available molybdenum.
Nickel (Ni)	0.2	2.0	Toxic to several plants at 0.5 to 1.0 mg/L; reduced toxicity at neutral or alkaline pH.
Selenium (Se)	0.02	0.02	Toxic to plants at low concentrations and to livestock if forage is grown in soils with low levels of added selenium.
Vanadium (V)	0.1	1.0	Toxic to many plants at relatively low concentrations.
Zinc (Zn)	2.0	10.0	Toxic to many plants at widely varying concentrations; reduced toxicity at increased pH (6 or above) and in fine-textured or organic soils.

After Fipps [62].

2.2.4. Kelly's Index

This is not a widely used index for assessing irrigation water quality. It is used to measure alkali hazards to crops. In Kelley's index, Ca and Mg is measured against Na^+ [26, 74, 75]. It is defined thus:

$$KI = [Na^+ /(Mg^{2+} + Ca^{2+})] \quad (8)$$

Usually, indices less than 1 indicates water of excellent quality for irrigation use. In contrast, indices more significant than 1, indicate water which is unsuitable for irrigation, because of alkali hazards.

2.2.5. Magnesium Hazard

Generally, Ca and Mg are found in a state of equilibrium in soils and groundwater aquifers. Mg concentrations in groundwater at levels greater than Ca hastens the degree of Mg saturation which destroys soil structure and reduces its productivity [59-61]. Preeminent Mg concentration in irrigation water affects the soil quality by converting it to alkali, which reduces crop yield. Waters having MH less than 50 are considered suitable for use. Irrigation waters having MH values greater than 50 are classified as unsuitable for irrigation. MH is defined thus:

$$MH = [Mg^{2+} x\ 100/(Ca^{2+} + Mg^{2+})] \quad (9)$$

2.2.6. Bicarbonate hazard

Bicarbonate hazard is usually expressed in terms of residual sodium carbonate (RSC). According to the United States, the Department of Agriculture (USDA), irrigation water having RSC values less than 2.5 is considered unsuitable for irrigation use. RSC index [76], is calculated thus;

$$RSC = [(HCO_3 + CO_3) - (Ca + Mg)] \quad (11)$$

Irrigation waters, having Pi values ranging from 1.25 to 2.5, are classified as permissible. Irrigation water having Pi values greater than 2.5 are classified as unsuitable. In irrigation waters having high concentrations of HCO_3, there is a propensity for Ca and Mg to precipitate as the water in the soil more concentrated. As a result, the relative proportion of water in the soil is increased in the form of sodium bicarbonate [77].

Table 6. Irrigation water classification in Sokoto Basin using chemical indices.

Parameter	Basement complex		Cretaceous-tertiary		Classification
	No. of samples	% of samples	No. of samples	% of samples	

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Kelly's index					
Less than 1	0	0	0	0	Suitable
Greater than 1	30	100	30	100	Unsuitable
Magnesium hazard					
Less than 50	8	26.67	10	33.33	Suitable
Greater than 50	22	73.33	20	66.67	Unsuitable
Permeability index					
Less than 25	0	0	0	0	Suitable
25-75	0	0	0	0	Good
Greater than 75	30	100	30	100	Excellent
Residual sodium carbonate					
Less than 1.25	27	90	20	66.67	Excellent
1.25-2.5	0	0	2	6.67	Permissible
Greater than 2.5	3	10	8	26.67	Unsuitable

2.3.Effects of low salinity in irrigation water

Irrigation water with an EC below 0.2 µS/cm can cause permeability problems as discussed in the previous section. Very low salinity water dilutes and leaks calcium and makes soil particles prone to fragmentation, triggering water permeation glitches [78]. Adding a calcium salt, such as gypsum or calcium chloride, to the irrigation water and raising the salinity to 0.2 to 0.3 µS/cm can avert infiltration problems. Refer to “Calculating rate of gypsum addition to irrigation water” to determine the amount of gypsum or calcium chloride needed to increase EC [78].

2.4.Absorption of some critical elements in irrigation water

Elements including selenium, molybdenum, and fluoride are allowed in plants, even though they are toxic to humans and animals (Figure 5). But elements such as lithium and boron can be toxic to plants. At levels > 0.5ppm, boron can be harmful to citrus, nuts, and deciduous fruits; cereals and cotton are moderately tolerant to boron, whereas alfalfa, beets, asparagus, and dates are relatively susceptible (1-2 ppm, boron). This element is found in most soaps and therefore may become a critical factor in the use of wastewater for irrigation purpose. Several other elements may be found in irrigation water and can cause toxic reactions in plants. Apart from sodium, chloride, and boron are of most concern. In areas where these ions are excessively high, they render water unsuitable for irrigations [78]. Crops grown on soils having an imbalance of calcium and magnesium may also exhibit toxic symptoms. Sulfate salts affect sensitive crops by limiting the uptake of calcium and increasing the adsorption of sodium and potassium, resulting in a disturbance in the cationic balance within the plant ([78]. The bicarbonate ion in soil solution harms the mineral nutrition of the plant through its effects on the uptake and metabolism of nutrients.

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Figure 5 (a) A 12-year-old girl is showing dental fluorosis at Dilchi- Dima village in the northeast basement areas. Fluoride content in water consumed is 3.14 mg/L. Coordinates: 10˚09.428'N and 12˚57.731'E and (b) Girls of ages (8 and 10) years old are showing dental fluorosis at Furzi, Jos east-north central Basement areas. Fluoride content consumed in groundwater is 7.2 mg/L, after Dibal, et al. [79].

High concentrations of potassium may introduce a magnesium deficiency and iron chlorosis. An imbalance of magnesium and potassium may be toxic. However, the effects of both can be reduced by high calcium levels [78]. Excess amounts of these nutrients in irrigation water may damage crops and limit crop rotation options. Irrigation waters differ widely in concentrations of nutrients. High concentrations of chloride or boron can damage crops [78]. Nitrogen in irrigation water should be withdrawn from the recommended fertiliser N to be applied to avoid excessive vegetative growth and succulence and to minimise nitrate leaching to groundwater. Nitrogen supplied by irrigation water can substitute for fertiliser N. Other nutrients provided by irrigation waters may also satisfy or exceed crop needs [78].

2.4.1. Boron

Table 7 shows the recommended limits of elements in irrigation water. Boron is one of the essential nutrients required by plants for healthy growth. However, it is only necessary for tiny quantities. It can, therefore, become poisonous to plants even at low concentrations (Figure 6). Boron toxicity symptoms can vary between types of plants species. Landscape plants typically first show a burning effect at the tips and edges on older leaves. In contrast, fruit and nut trees may not show those leaf symptoms but rather show ooze or cankers on limbs or trunk [80]. Crop groups of boron tolerance have been summarised in Table 7. While boron is an essential element for plants and low conditions directly impact plant growth and yield by limiting crop productivity, considerable amounts of boron are toxic to plants and reduce crop yield [81].

Table 7. Boron tolerance by crop groups

(a) Sensitive (1.0 mg/l B)	**(b) Semi-tolerant (2.0 mg/l B)**	**(c) Tolerant (4.0 mg/l B)**
Pecan	Sunflower (native)	Athel (Tamarix aphylla)

Walnut (Black, Persian or English	Potato	Asparagus
Jerusalem artichoke	Cotton (Acala and Pima)	Palm (Phonix canarieensis)
Navy bean	Tomato	Date palm
American elm	Sweetpea	Sugar beet
Plum	Radish	Mangel
Pear	Filed pea	Garden Beet
Apple	Ragged Robin rose	Alfalfa
Grape (Sultania and Malaga)	Olive	Gladiolus
Kadota fig	Barley	Broad bean
Persimmon	Wheat	Onion
Cherry	Corn	Turnip
Peach	Milo	Cabbage
Apricot	Oat	Lettuce
Thornless blackberry	Zinnia	Carrot
Orange	Pumpkin	
Avocado	Bell pepper	
Grapefruit	Sweet potato	
Lemon	Lima bean	

After [62].

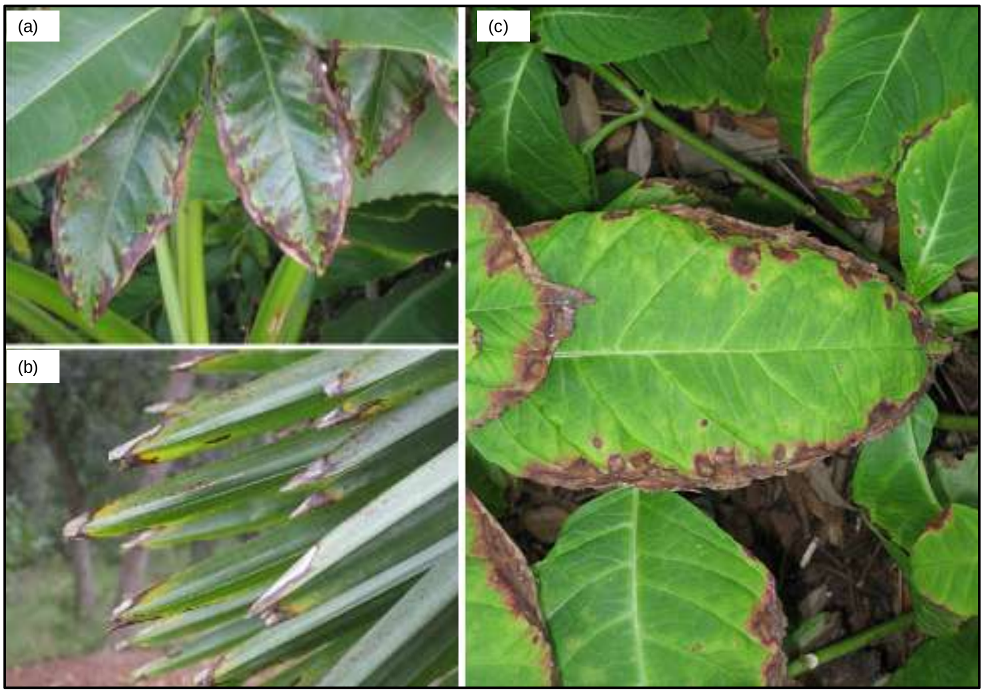

Figure 6. Boron toxicity symptoms in plants.

However, boron is also an advantageous and essential element for humans and animals. It is a vital mineral for human nutrition because it helps in maintaining cell membrane functions and enzyme activities [81]. In conjunction with other minerals, such as Ca, Mg and vitamin D,

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boron aids to avert osteoporosis and osteoarthritis and enhance the immune system and inflammatory and hormonal responses. Even though a recommended daily dose has not been specified, 3 mg per day is mainly suggested as a nutrient supplement. Boron deficit symptoms have correlated very strongly to the bone and immune system and inflammatory and hormonal responses [81]. Despite all these benefits, once well water is polluted by high boron concentrations, no remedies for well water. Unfortunately, there is nothing one can do to reduce its level in well water; therefore, selecting boron-tolerant plants is a wise idea [80]. Table 8 shows the classification of irrigation water base on boron concentrations.

Table 8. Irrigation water classification base on boron concentration.

Classification	Group of crops			
	Sensitive	Semi-tolerant	Tolerant	Remarks
Class 1	<0.33	<0.67	<1.00	Excellent
Class 2	0.33-0.67	0.67-1.33	1.00-2.00	Good
Class 3	0.67-1.00	1.33.2.00	2.00-3.00	Permissible
Class 4	1.00-1.25	2.00-2.50	3.00-3.75	Doubtful
Class 5	>1.25	>2.5	>3.75	Unsuitable

After [62]

Existing knowledge about the toxic level of boron in humans needs to be improved. The inadequate data on this topic has only been obtained from human poisoning cases and toxicity studies on animals. Based on these reports, data from accidental poisonings show that the severe lethal dose of boric acid is 3000-6000 mg for infants and 15,000-20,000 mg for adults [82]. Clinical effects include irritability, seizures, and gastrointestinal disorders. Some studies showed inflammation, congestion, exfoliation of the mucosa, exfoliative dermatitis, findings of cloudy swelling and granular degeneration of renal tubular cells and edema. Clinical symptoms of boron toxicity have been described within the dose range of 100 to 55,500 mg depending on age/body weight. Inter-individual variability seems to be high [82].

2.4.1.1. Removal of Boron from irrigation waters

Boron is extensively distributed in natural waters as well as in soils. This element is one of the seven essential micronutrients required for the average growth of most plants [83]. But if it is present in excessive amounts may cause toxicity. There is a comparatively small range between levels of soil boron, causing deficiency and toxicity symptoms in plants. Recently, a significant increase in the concentration of boron in surface and groundwaters has been observed, restraining the use of water for irrigation purposes. Boron concentration ranging from 1.0 and 4.0 µg of B/mL of water produce cellular necrosis, affecting the biological functioning and crop yields [83]. Before applying boron-rich water in irrigation fields, particularly in soils with previously limiting physicochemical environments, a treatment to remove boron and other related problems are required. The use of Diammonium phosphate $(NH_4)_2PO_4$ and calcium hydroxide $Ca(OH)_2$ in the elimination of boron, through the formation of hydroxyapatite (HAp), is an effective approach. In addition, the effect of two flocculants (calcium sulfate ($CaSO_4.2H_2O$) and aluminium sulfate ($Al_2(SO_4)_3$) at concentrations of 35% w/v to fast-track the precipitation of calcium borate hydroxide, resulting from the formation of HAp (Ventura et al., 2018). Experiments showed that boron elimination starts to occur at 30 minutes of the reaction time, after Ca(OH)2 + $(NH4)_2HPO_4$ were added [83]. Extra elimination

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of boron can be obtained when flocculants are added, mainly when gypsum is used. Results showed that boron concentration reduced from 18 ppm to about 8.5 ppm after 30 minutes and to about 3 ppm after 4 hours (Figure 7), corresponding to a removal of about 80% as compared to the initial concentration.

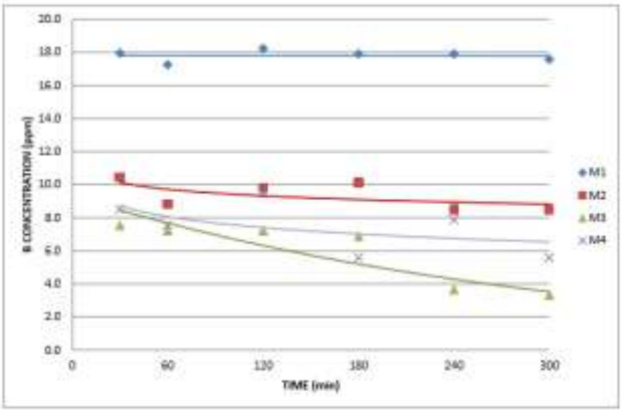

Figure 7. Boron removal from water, using diammonium phosphate $(NH_4)_2PO_4$ and calcium hydroxide $Ca(OH)_2$, and the effect of two flocculants: Calcium sulfate CaSO4.2H2O and aluminium sulfate $Al2(SO4)_3$ After Ventura, et al. [83].

For lesser initial absorptions (5 µg of B/mL) boron content was reduced to about 0.98 µg of B/mL. The results further showed that the use of $Ca(OH)_2$ + $(NH_4)_2HPO_4$ in addition to the use of gypsum ($CaSO_4.2H_2O$) at 35 % w/v) is an alternative method for treating water and lessen boron to values acceptable for crop irrigation [83]. However, pH also needs to be adjusted before a recommendation can be made. After the elimination process, the pH of the solution was about 11.5, and adjustment was needed to lower the pH to values acceptable for crop production. To achieve this, an explanation of H_2SO_4 0.408N can be added to reduce the pH level [83].

2.4.2. Chloride

Chloride contributes to the salinity of irrigation water, and when concentrations are very high, can be toxic to plants. Excess chloride deposited on leaves causes a foliar burn. Some plants are more susceptible to chloride than others (Table 9). Damage caused by high-chloride in irrigation water can be minimised by planting a less sensitive crop; avoiding foliar contact by using furrow, flood, or drip irrigation; and rinsing the plants at the end of each irrigation event if a source of high-quality water is available [78]. Burnt leaves can be caused by chlorine toxicity in plants. Chlorine is a micronutrient, vital to plant growth. Though, too much chlorine can accrue in leaf tissue, forming leaves with a burned appearance (Figure 8).

Table 9. Irrigation water classification base of chloride.

Chloride (mg/l)	Effects on crops	Susceptible plant
<70	Safe for most crops	Rhododendron, azalea, blueberry, dry beans
70-140	Sensitive crops	Onion, mint, carrot, lettuce, pepper, grape, raspberry

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140-350	Show injury	Potato, alfalfa, sudangrass, squash, wheat, sorghum, corn, tomato
>350	Causes severe problems	Sugarbeet, barley, asparagus, cauliflower

After Hopkins, et al. [78]

Plants with burnt leaves have brown or dead tissue on the tips, margins, or between the veins of the leaf. Leaf tissue may appear bleached, instead of scorched. Greeneries may be smaller than usual. They may be yellow and drop early. Chlorine toxicity can result from air pollution, in the form of chlorine gas, or from excess chloride in the soil. Surplus chloride can build up in the soil from swimming pool runoff, irrigation water, or excess soil salts. Chlorine converts to chloride in the soil and is absorbed by crops in this form. Chloride toxicity is more pronounced in irrigated, dry regions, seacoast areas, and near roads frequently treated with salt in the wintertime. Chloride concentrations can be reduced with the use of gypsum. Incorporate gypsum into the soil at a rate of 58 lbs. per 1000 square feet, in loam soils. Low gypsum is required in sandy soils, more in heavy clay soils. Water thoroughly to leak toxic levels of chlorine from the soil.

Injury to plants from chlorine gas is less common than damage from other air contaminants, such as sulfur dioxide, fluoride, and ozone. Chlorine gas is a by-product in the production or burning of glass, plastics, paints, and stains. It is released from refineries or as a result of chemical spills. Reducing air pollution at its source is the best solution to minimise damage to plants and people. Careful watering practices can reduce air pollution damage to plants. Soil should be dry during periods of exposure to air pollutants, followed by thorough watering after exposure. Wetting the leaves of sensitive plants may help to reduce damage during periods of low air quality. Trees sensitive to chlorine are ash, boxelder, Siberian crabapple, dogwood, horse-chestnut, silver maple, sugar maple, pin oak, sweetgum, and yellow-wood.

Figure 8. Chloride toxicity in plants

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2.4.2.1. Removing chloride from irrigation waters

Chlorides are the natural substances which are found in the water bodies in varying amounts, and its concentration in natural waters is significantly low. However, the industrial, domestic and agricultural wastewaters that are generated from anthropogenic sources, may contain a large volume of chlorides, which can cause a significant disturbance in the ecological balance [84]. Many techniques are used to reduce the number of chlorides in wastewater like demineralisation, reverse osmosis, coagulation, precipitation, electrodialysis and so on. Reverse osmosis is the most widely used technique of reducing chloride from irrigation water (Figure 9).

Typically, water derived from a tube well is high in sodium chloride 'salts'. Sodium will retain moisture in the soil, creating arid circumstances, and subsequently obstructing the intake of nutrients by the plants. Chlorides, on the other hand, are highly soluble in water and can be absorbed by plants which can cause damaging effects. High levels of chlorides in plants cause toxicity and can result in stunted discoloured foliage, leaf scorch, and twig dieback. The robust and dense polymer membranes in reverse osmosis systems can filter out impurities with ease. Inside the membrane cover, controlled levels of pressure are applied to the feed water, forcing water through the membranes. This separates the impurities from the water, resulting in highly purified product water.

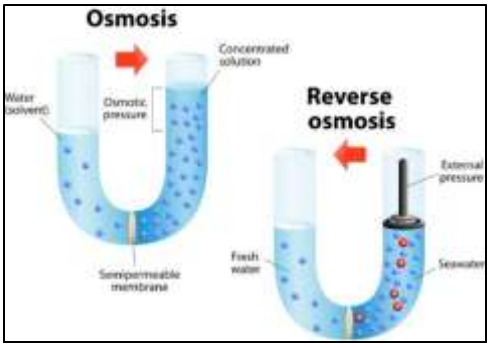

Figure 9. Reverse osmosis

This method remains one of the most efficient and economically viable forms of water treatment when attempting to reduce levels of sodium chloride and other impurities in irrigation waters because it allows farmers to use private water sources without the worry or hassle of low water quality. This method is also beneficial to the agriculture industry as it allows for lower levels of contaminants and the controlled injection of nutrients ensuring an increase in production which equates to a quicker return on the farmer's investment into reverse osmosis. It works by passing water through a semi-permeable membrane that separates pure water into one stream and saltwater into another stream. In regular osmosis water flows from a lower concentration of salts to higher concentrations; in reverse osmosis the application of pressure more significant than the osmotic pressure reverses the water flow from higher concentrations too much lower concentrations, producing pure water. With this method, about 50% of water can be recovered as pure water, while about 50% becomes salty wastewater.

2.5. Nitrogen and other nutrients

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Irrigation water may supply substantial amounts of nitrogen and other nutrients. Recycled surface irrigation waters often are rich in nutrients. Irrigation water derived from rivers usually contains lesser nutrient concentrations. Application of excessive amounts of N can reduce crop quality through several mechanisms:

i. Excess N generates excess vegetative growth at the expense of crop yield and impacts maturity, quality, and storability, which is essential for crops such as potatoes, grass seed, sugar beets, and apples; and
ii. Excess N results in a more succulent plant, which may be more susceptible to insects, pathogens, and frost damage.

The concentration of N in the irrigation water, yield and yield components could be represented by a curve similar to the law of diminishing returns [85]. In conventional fertilisation, the optimum output can be achieved at an N concentration of about 5 mg/l. However, this is the limit in the present system of agricultural technology. In this case, the impact on plants and soil should be minimised. The level of total-nitrogen concentration for the direct utilisation of sewage water with secondary processing can be fixed at values ranging for 3.0 to 4.0 mg/l based on the lodging index, yield and yield components, with a maximum concentration of 5.0 mg/l [85].

2.6.Salt-affected soils (sodic)

Soil salinity is a massive problem for agriculture under irrigation. In the arid and semi-arid regions, the soils are often saline with low agricultural productivity. In these areas, most crops are grown by irrigation, and to aggravate the problem, poor irrigation management can lead to secondary salinisation that affects 20% of irrigated land worldwide. All soils hold some water-soluble salts. Plants engross vital nutrients in the form of soluble salts, but extreme build-up overturns the plant growth. Both EC and SAR are commonly used to classify salt-affected soils (Table 10).

Table 10. Classification of salt-affected soils based on analysis of saturation extracts.

Standard	Normal	Saline	Sodic	Saline-sodic
EC (μS/cm)	<4	>4	<4	>4
SAR	<13	<13	>13	>13

After [62]

Saline soils usually have a pH value below 8.5, are relatively low in sodium and contain principally Na, Ca, Mg, Cl, and SO_4. These compounds cause the white coating which forms on the surface and the salt streaks along the furrows. The compounds which cause saline soils are very soluble in water; therefore, leaching is very useful in reclaiming these soils. Sodic soils generally have a pH value between 8.5 and 10 [62]. These soils are known as ‘black alkali soils’ because of their darkened appearance and smooth, slick-looking areas caused by the dispersed condition. In sodic soils, Na has destroyed the permanent structure which tends to make the soil impermeable to water. Consequently, leaching alone will not be effective unless

Reducing salts in irrigation waters

Salinisation can be controlled by leaching of salt from the root zone, transformed farm management practices and the use of salt-tolerant plants. Irrigated farming can be sustained by better irrigation practices such as the adoption of partial rootzone drying methodology, and

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drip or micro-jet irrigation to optimise the use of water [86]. The spread of dryland salinity can be contained by reducing the amount of water passing beyond the roots. This can be done by re-introducing deep-rooted perennial plants that continue to grow and use water during the seasons that do not support annual crop plants. This may restore the balance between rainfall and water use, thus preventing rising water tables and the movement of salt to the soil surface.

Farming schemes can change to integrate perennials in rotation with annual crops (phase farming), in mixed plantings (alley farming, intercropping), or site-specific plantings (precision farming). Though the use of these methods to sustainable management can upgrade yield reduction under salinity stress, implementation is often limited because of cost and availability of good water quality or water resource [86]. Developing efficient, low cost, easily flexible approaches for abiotic stress management is a significant challenge. Universally, wide-ranging research is being carried out, to develop methods to cope with abiotic stresses, through the development of salt and drought-tolerant varieties, shifting the crop calendars, resource management practices etc. as illustrated in Figure 10.

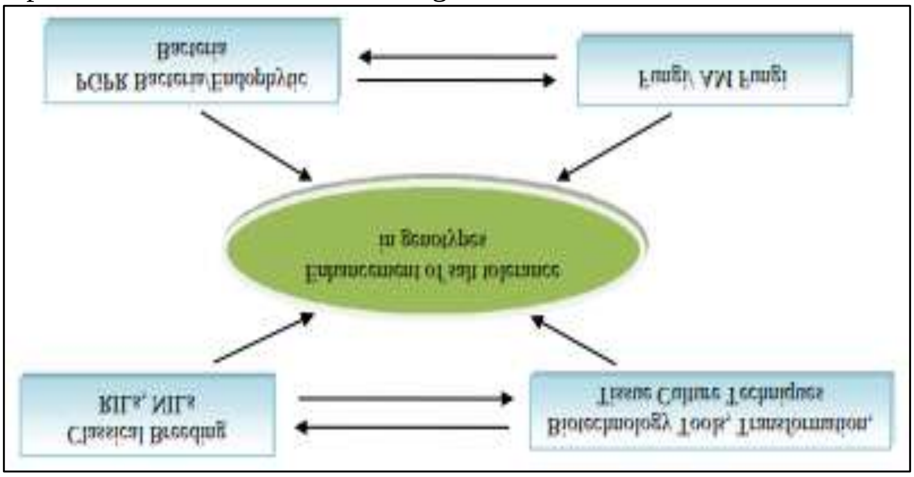

Figure 10. Methods for enhancement of salt tolerance in crops [86].

Amendments are composed of sulfur in its elemental form or related compounds such as sulfuric acid and gypsum. Gypsum also contains Ca, which is an essential element in correcting these conditions [62]. Some chemical amendments render the natural calcium in the soil more soluble. As a result, Ca replaces the adsorbed Na, which helps restore the infiltration capacity of the soil. Polymers are also beginning to be used for treating sodic soils. It is important to note that the use of amendments does not eliminate the need for leaching. Excess water must still be applied to leach out the displaced Na. Chemical modifications are only effective on sodium-affected soils. Amendments are ineffective for saline soil conditions and often will increase the existing salinity problem [62]. Table 11 outlines the most common amendments.

Table 11. Many amendments for recovering sodic soil and amount equivalent to gypsum.

Amendment	**Physical description**	**Amount equivalent to 100% gypsum**
Gypsum	White mineral	1.0
Sulphur	Yellow element	0.2
Sulphuric acid	Corrosive liquid	0.6
Lime sulfur	Yellow-brown solution	0.8

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Calcium carbonate	White mineral	0.6
Calcium chloride	White salt	0.9
Ferrous sulfate	Blue-green salt	1.6
Pyrite	Yellow-black salt	0.5
Ferric sulfate	Yellow-brown salt	0.6
Aluminium sulphate	Corrosive granules	1.3

After Fipps [62].

2.7.Salinity and growth stage

Various crops have a slight tolerance for salinity during seed germination, but weighty tolerance during later growth stages. Some crops such as barley, wheat, and corn are known to be more sensitive to salinity during the early growth period than in germination and later growth stages. Sugar beet and safflower are comparatively more sensitive in germination. At the same time, the tolerance of soybeans may rise or decline during different growth periods depending on the variety [62].

2.8. Leaching for salinity control

Soluble salts that accrue in soils must be leached below the crop root zone to maintain productivity. Leaching is an essential management tool for regulating salinity. Water is applied in a surplus of the total amount used by the crop and lost to evaporation. The approach is to keep the salts in solution and flush them below the root zone. The amount of water required is referred to as the leaching requirement or the leaching fraction. Surplus water may be applied to every irrigation to provide the water needed for leaching [62]. However, the time interval between leaching does not appear to be critical if those crop tolerances are not surpassed. So, leaching can be accomplished with each irrigation, every few irrigations, once yearly, or even longer depending on the severity of the salinity problem and salt tolerance of the crop [62]. A sporadic or annual leaching event where water is ponded on the surface is an easy and effective method for controlling soil salinity. In some areas, average rainfall provides adequate leaching.

2.9. Determining essential leaching fraction

The leaching fraction is generally calculated using the following relationship:

$$LF = \frac{EC_{iw}}{EC_e} \qquad (10)$$

where *LF* = leaching fraction - the fraction of applied irrigation water that must be reached through the root zone *ECiw* = electric conductivity of the irrigation water *use* = the electric conductivity of the soil in the root zone.

Equation 10 can be used to compute the leaching fraction required to maintain the root zone at a stressed salinity condition. If the amount of water obtainable for leaching is fixed, then the equation can be used to compute the salinity level that will be maintained in the root zone with that amount of leaching. It is imperative to note that Equation 5.10 abridges a complex soil water process. EC should be checked sporadically, and the amount of leaching attuned accordingly. Based on this equation.10, Table 12 outlines the amount of leaching required for diverse classes of irrigation waters to maintain the soil salinity in the root zone at the desired level [62]. Yet, supplementary water must be provided because of the wastefulness of irrigation systems (Table 13), as well as to remove the existing salts in the soil.

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Table 12. Leaching prerequisite as related to the salinity of the irrigation water.

The conductivity of irrigation water (µS/cm)	**Leaching requirement based on the specified maximum values for EC of the drainage water at the bottom of the root zone**			
	4 (µS/cm)	**8 (µS/cm)**	**12 (µS/cm)**	**16 (µS/cm)**
	%	**%**	**%**	**%**
0.75	13.3	9.4	6.3	4.7
1.00	25.0	12.5	8.3	6.3
1.25	31.3	15.6	10.4	7.8
1.50	37.5	18.7	12.4	9.4
2.00	50.0	25.0	16.7	12.5
2.50	62.5	31.3	20.8	15.6
3.00	75.0	37.5	25.0	18.7
5.00	-	62.5	4.7	31.2

After Fipps [62].

Table 13. Typical overall on-farm efficiencies for various types of irrigation systems.

System	Overall efficiency (%)
Surface	50-80
a. average	50
b. land leveling and delivery pipeline meeting design standards	70
c. tailwater recovery with (b)	80
d. surge	60-90*
Sprinkler (moving and fixed systems)	55-85
LEPA (low-pressure precision application)	95-98
Drip	80-90**

Note: Surge has been found to increase efficiencies 8 to 28% over non-surge furrow systems. **Drip systems are typically designed at 90% efficiency, short laterals (100 feet) or systems with pressure compensating emitters may have higher efficiencies. After Fipps [62].

2.10. Other salinity management techniques

Methods for controlling salinity that need comparatively minor changes are more frequent irrigations, selection of more salt-tolerant crops, additional leaching, pre-plant irrigation, bed forming and seed placement [62]. Alternatives that require significant management changes are changing the irrigation method, altering the water supply, land-levelling, modifying the soil profile, and installing subsurface drainage.

4.5. Residue management

The famous proverb ‘salt loves bare soils’ refers to the fact that infertile soils have higher evaporation rates than those covered by residues. Residues left on the soil surface decrease evaporation. Thus, fewer salts will accrue, and rainfall will be more effective in providing for leaching [62]. More frequent irrigations salt concentrations rise in the soil as the crop removes water. Characteristically, salt concentrations are lowest following an irrigation and higher just before the next irrigation. Increasing irrigation frequency maintains a more

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constant moisture content in the soil. Thus, most of the salts are then kept in solution, which aids the leaching process. Surge flow irrigation is often effective at reducing the minimum depth of irrigation that can be applied with furrow irrigation systems. Consequently, a larger number of irrigations are possible using the same amount of water [62].

4.6. Mitigation of abiotic stress in crops by rhizospheric bacteria

In addition to developing mechanisms for stress tolerance, bacteria can also impart some degree of tolerance to plants towards abiotic stresses like drought, chilling injury, salinity, metal toxicity and high temperature [86]. Nowadays, bacteria belonging to different species including *Rhizobium, Bacillus, Pseudomonas, Pantoea, Paenibacillus, Burkholderia, Achromobacter, Azospirillum, Microbacterium, Methylobacterium, Variovorax, Enterobacter* etc. have been reported to provide tolerance to host crops under diverse abiotic stress situations. The Use of these bacteria, for example, can ease stresses in agriculture, thus opening a new and emerging application of microorganisms. Bacterial caused stress tolerance in crops may be due to a diversity of mechanisms proposed from time to time based on studies done [86]. Production of indoleacetic acid, gibberellins and some unknown determinants by PGPR, results in amplified root length, root surface area and several root tips, resulting into an improved uptake of nutrients thus improving crop health under stress circumstances.

Crop growth-promoting microbes have been found to expand the growth of tomato, pepper, canola, bean, and lettuce under saline circumstances. Some PGPR strains produce cytokinin and antioxidants, which result in abscisic acid (ABA) build-up and dilapidation of volatile oxygen species. High activities of antioxidant enzymes are connected to oxidative stress tolerance. Another PGPR strain, *Achromobacter piechaudii* ARV8, which formed 1-aminocyclopropane-1-carboxylate (ACC) deaminase, conferred IST against drought and salt in pepper and tomato [86]. Ethylene levels control some features of crop life, and the biosynthesis of ethylene is laid open to tight regulation, including transcriptional and post-transcriptional factors controlled by ecological cues, as well as biotic and abiotic stresses. Under stress environments, the crop hormone ethylene endogenously regulates crops homeostasis and result in abridged root and shoot growth [86]. In the existence of ACC deaminase producing bacteria, plant ACC is sequestered and degraded by bacterial cells to supply nitrogen and energy. Also, by removing ACC, the bacteria decrease the harmful effect of ethylene, amending stress and promoting crop growth (Shrivastava and Kumar, 2015).

The compound and dynamic connections among microbes, roots, soil, and water in the rhizosphere bring changes in physicochemical and mechanical properties of the (Shrivastava and Kumar, 2015). Bacterial polysaccharides can bind soil particles to form microaggregates and macroaggregates. Crop roots and fungal hyphae fit in the holes between microaggregates and thus stabilise macroaggregates [86]. Crop treated with Exo-poly saccharides (EPS) creating bacteria show augmented resistance to water and salinity stress due to better soil structure. EPS can also bind to cations, including Na consequently making it inaccessible to crops under saline environments.

Improved production of proline along with reduced electrolyte drip, maintenance of relative water content of leaves and selective uptake of K ions caused in salt tolerance in Zea mays co-inoculated with *Rhizobium and Pseudomonas*. Rhizobacteria occupying the sites exposed to recurrent stress circumstances, are expected to be more adaptive or tolerant and may serve as better crop growth promoters under stressful situations. Similarly, inoculation with *P. putida* Rs 198 helped cotton growth and germination under conditions of salt stress [86].

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PGPRs, which can solubilise PO_4, produce phytohormones and siderophores in salt condition promotes the growth of tomato plants under 2% NaCl stress.

Also, the production of proline, shoot/root length, and dry weight were also higher in soybean plants inoculated with these isolates under induced salt stress. Similarly, the impact of PGPR inoculation on growth and antioxidant status of wheat under saline conditions indicate that co-inoculation with *B. subtilis* and *Arthrobacter sp*. could ease the adverse effects of soil salinity on wheat growth with an increase in dry biomass, total soluble sugars and proline content [86]. *P. pseudoalcaligenes*, an endophytic bacterium in combination with a *rhizospheric B. pumilus* in paddy was able to shield the crops from abiotic stress by the introduction of osmoprotectant and antioxidant proteins than by the rhizospheric or endophytic bacteria alone at early stages of growth.

Crops vaccinated with endophytic bacterium *P. pseudoalcaligenes* showed a suggestively higher concentration of glycine betaine-like quaternary compounds and higher shoot biomass at lower salinity levels. Whereas at higher salinity levels, a mixture of both *P. pseudoalcaligenes* and *B. pumilus* showed improved response against the adverse effects of salinity [86]. The result of the injection of Azospirillum strains isolated from saline or non-saline soil on yield and yield components of wheat in salinity showed that vaccination with the two isolates improved salinity tolerance of wheat plants; the saline-adapted hermit expressively augmented shoot dry weight and grain yield under severe water salinity. The effect of injection of Azospirillum strains isolated from saline or non-saline soil on yield and yield components of wheat in salinity showed that vaccination with the two isolates improved salinity tolerance of wheat plants; the saline-adapted hermit expressively augmented shoot dry weight and grain yield under severe water salinity.

The constituent of grain yield most affected by inoculation was grains per plant. Crops inoculated with saline-adapted Azospirillum strains had higher N absorptions at all water salinity levels. The plant growth-promoting the activity of an auxin and siderophore producing isolate of Streptomyces under saline soil environments showed increases in the growth and expansion of the wheat plant [86]. There were substantial upsurges in germination rate, percentage, and consistency, shoot length and dry weight related to the control. Applying the bacterial inocula augmented the concentration of N, P, Fe and Mn in wheat shoots grown in average and saline soil, suggesting that Streptomyces isolate has potential to be used as bio fertilisers in saline soils [86].

Table 14. Role of plant growth-promoting bacteria in salinity stress alleviation in plants.

Achromobacter piechaudi	Tomato (Lycopersicon esculentun)	Reduced levels of ethylene and improved plant growth	Mayak et al. (2004)
Azospirillum	Maise (Zea mays)	Restricted Na uptake and increased K and Ca uptake along with increased nitrate reductase and nitrogenase activity	Hamdia et al. (2004)
Aeromonas hydrophila/caviae Bacillus insolitus, Bacillus sp.	Wheat (Triticum aestivum)	Exopolysaccharide production	Ashraf (2004)

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Pseudomonas syringae, Pseudomonas fluorescens, Enterobacter aerogenes	Maise (Zea mays)	ACC deaminase activity	Nadeem et al. (2007)
Pseudomonas fluorescens	Groundnut (Arachis hypogea)	Enhanced ACC deaminase activity	Saravana Kumar and Samiyappan (2007)
Bacillus subtilis	Arabidopsis thaliana	Tissue-specific regulation of sodium transporter HKT1	Zhang et al. (2008)
Pseudomonas mendocina	Lettuce (L. Sativa L. cv. Tafalla)	ACC deaminase activity and enhanced uptake of essential nutrients	Kohler et al. (2009)
Rhizobium, Pseudomonas	Maize	Decreased electrolyte leakage and, increase in proline production, maintenance of relative water content of leaves, and selective uptake of K ion	Bano and Fatima (2009)
Pseudomonas pseudoalcaligenes, Bacillus pumilus	Rice (Oryza sativa)	The increased concentration of glycine betaine (compatible solute)	Jha et al. (2011)
Pseudomonas putida Rs-198	Cotton	Increase the absorption of the Mg, K and Ca and decrease the uptake of the Na from the soil	Yao et al. (2010)
PGPR (Mk1, Pseudomonas syringae; Mk20, Pseudomonas fluorescens; and Mk25, Pseudomonas fluorescens biotype G) and Rhizobium phaseoli strain M1, M6, and M9	Mung bean	ACC deaminase activity and improvement in growth and nodulation in mung bean	Ahmad et al. (2011)
Raoultella planticola Rs-2	Cotton	ACC deaminase activity	Wu et al. (2012)
Brachybacterium saurashtrense (JG-06), Brevibacterium casei (JG-08), and Haererohalobacter (JG-11)	Groundnut (Arachis hypogaea L.)	High K/Na ratio and higher Ca, phosphorus, and nitrogen content	Shukla et al. (2012)
Rhizobium phaseoli and PGPR (Pseudomonas syringae, Mk1;	Mung bean (Vigna radiata L.)	ACC deaminase activity and increased water use efficiency	Ahmad et al. (2012)

Pseudomonas fluorescens, Mk20 and Pseudomonas fluorescens Biotype G, Mk25)			
Rhizobium and Pseudomonas	Mung bean (Vigna radiata L.)	IAA production and ACC deaminase activity	Ahmad et al. (2013)
Pseudomonas putida, Enterobacter cloacae, Serratia ficaria, and Pseudomonas fluorescens	Wheat	Enhanced germination percentage, germination rate, and index and improved the nutrient status of the wheat plants	Nadeem et al. (2013)
Pseudomonas pseudoalcaligenes and Bacillus pumilus	Salt sensitive rice GJ-17	Reduce lipid peroxidation and superoxide dismutase activity	Jha and Subramanian, 2014
Acinetobacter spp. and Pseudomonas sp.	Barley and oats	Production of ACC deaminase and IAA	Chang et al. (2014)
Streptomyces sp. strain PGPA39	'Micro-Tom' tomato	ACC deaminase activity and IAA production and phosphate solubilisation	Palaniyandi et al. (2014)

After Shrivastava and Kumar [86].

Studies on the effect of five plant growth-promoting halotolerant microbes on wheat growth have shown that inoculation of those halotolerant microbial strains to amend salt stress (80, 160 and 320 mM) in wheat seedlings produced an increase in root length of 71.7% in comparison with uninoculated positive controls. In particular, *Hallobacillus sp*. and *B. halodenitrificans* displayed more than 90% growth in root elongation and 17.4% growth in dry weight when compared to uninoculated wheat seedlings at 320 mM NaCl stress signifying an essential decrease of the harmful effects of NaCl [86]. Findings show that halotolerant bacteria isolated from saline surroundings have the potential to improve crop growth under saline stress through direct or indirect mechanisms and would be most suitable as bio inoculants under such environments. The separation of native bacteria from the stress affected soils and screening based on their stress tolerance. PGP traits may be useful in the quick assortment of efficient strains that could be used as bio inoculants for stressed crops [86]. Some of the developments and investigations carried out in assessing the role of rhizobacteria as salinity stress remediators have been potted in Table 13.

3. RECENT ADVANCES IN GROUNDWATER POLLUTION MODELLING

In the race to improve agricultural output, irrigation will become more reliant on ill characterised and practically unmonitored sources of water. Enhanced use of irrigation water has led to decreased moisture and soil quality in various regions [20]. Traditionally, soil salinisation and lessened crop efficiency have been the central focus of irrigation water quality. Not long ago, there is a growing indication for the existence of geogenic pollutants in water [20]. The emergence of trace elements and an upsurge in the utilisation of wastewater has

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emphasised the susceptibility and intricacies of the composition of irrigation water and its role in guaranteeing proper crop growth, and long-term food quality [20].

Critical skills of gauging vanishingly small absorptions of biologically-active organic pollutants, comprising of steroid hormones, pharmaceuticals, plasticisers, and personal care products, in many types of irrigation water sources offer the means to assess uptake and incidence in crops. However, they do not answer questions associated with food safety or human health effects [20]. Synthetic and natural nanoparticles are now proven to appear in various water sources, possibly altering plant growth and food quality. The speedily changing condition of irrigation water instantly needs closer consideration to identify and foretell long-term paraphernalia on soils and food crops in a progressively fresh-water stressed world.

4. CONCLUSION

In this review, an attempt has been made to discuss the causes, effects, and remediation of salinity in irrigated fields. This was followed by an analysis of significant ions affecting irrigation water quality. Specifically, elements including boron, chloride, and nitrogen are hazardous into crops. Therefore, it is essential to identify their sources, effects, and how they can be removed from irrigation waters. Application of chemical indices including sodium adsorption ratio, sodium percent, residual sodium carbonate, magnesium hazard and permeability index in irrigation water analysis was recommended. The review also highlights the crop tolerance in saline conditions and tolerance limits of individual crops to salinity. This should be monitored for improved irrigation scheme performance. This has necessitated the application of salinity management techniques in irrigation water.

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