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Satish Manda
 Maharana Pratap
 Horticultural University,
 Karnal, Haryana, India

Manish Kumar
 Maharana Pratap
 Horticultural University,
 Karnal, Haryana, India

Rajeev Kumar Yadav
 Dr. Rajendra Prasad Central
 Agricultural University, Pusa,
 Bihar, India

Satyapal Singh
 Maharana Pratap
 Horticultural University,
 Karnal, Haryana, India

Harjot Singh Sidhu
 Maharana Pratap
 Horticultural University,
 Karnal, Haryana, India

Corresponding Author:
Satish Manda
 Maharana Pratap
 Horticultural University,
 Karnal, Haryana, India

Salinity and vegetable production in context to nematodes: A review on understanding crop responses and irrigation management

Satish Manda, Manish Kumar, Rajeev Kumar Yadav, Satyapal Singh and Harjot Singh Sidhu

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Abstract

Water scarcity and soil salinization are major challenges for global agricultural sustainability, particularly in arid and semi-arid regions where vegetable production is essential for food security and nutritional needs. With approximately 950 million hectares of land affected by salinity worldwide, the strategic utilization of saline water resources may emerge as a viable alternative to conventional freshwater irrigation to resolve the salinity issue. This comprehensive review examines the multifaceted approaches to successfully implementing saline water irrigation in vegetable production systems. This study synthesizes current knowledge on salt stress mechanisms in plants, physiological responses of major vegetable crops to salinity, and innovative management strategies including advanced irrigation technologies, soil amelioration practices, plant-based interventions, and microbial solutions. Special emphasis is placed on practical management techniques such as drip irrigation systems, leaching fraction management, water blending strategies, chemical and organic amendments, grafting technology, seed priming, and the application of plant growth-promoting rhizobacteria. This review provides research-based recommendations for optimizing saline water use in vegetable production while maintaining crop productivity, soil health, and long-term sustainability.

Keywords: Saline water, salinity, vegetable production, drip irrigation, electrical conductivity, irrigation management

1. Introduction

Global agriculture faces an unprecedented water crisis driven by population growth, urbanization, climate change, and increasing demand for freshwater among various sectors. As maximum share of global freshwater withdrawals is allocated to agriculture and this share may increase substantially in coming decades. In this context, the exploration of alternative water sources, particularly saline water, has become imperative for maintaining agricultural productivity and ensuring food security.

Soil salinity has also significantly affected agricultural land globally, with salinization increasing at very alarming rate. Primary salinization results from natural processes such as weathering of parent materials and capillary rise of saline groundwater, while secondary salinization is predominantly caused by anthropogenic activities including improper irrigation management, inadequate drainage, and the use of poor-quality irrigation water.

Vegetables constitute an essential component of human nutrition, providing vital vitamins, minerals, antioxidants, and dietary fibre. However, most vegetable crops exhibit moderate to high sensitivity to salinity stress, with threshold electrical conductivity (EC) values ranging from 1.0 to 2.5 dS/m in saturated soil extracts^[15]. Despite this inherent sensitivity, strategic management approaches can enable successful vegetable production using saline irrigation water under specific conditions. Recent advances in irrigation technology, particularly drip irrigation and precision agriculture, have created new opportunities for utilizing saline water resources safely and efficiently. Studies conducted across different agroecological zones have demonstrated that with appropriate management practices—including proper irrigation scheduling, leaching fraction application, soil amendment incorporation, and selection of moderately tolerant varieties—vegetable crops can maintain acceptable yields even when irrigated with saline water having electrical conductivity levels of 4-6 dS/m^[3, 4].

Therefore, development of integrated management strategies combining multiple approaches offers the greatest promise for sustainable saline water utilization. This review comprehensively examines the state of knowledge regarding saline water application in vegetable production, synthesizing findings from recent field experiments, greenhouse studies, and modeling approaches.

2. Salinity in Irrigation Water

Salinity in irrigation water refers to the presence of dissolved salts, primarily composed of ions such as sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) though small quantities of salts are normal in most water sources, excessive salinity can adversely affect soil health, crop productivity, and irrigation infrastructure. Quantification of salinity and other parameters of salinity are discussed in this part.

2.1 Salinity Parameters and Water Quality

Irrigation water quality is primarily assessed through several key parameters that collectively determine its suitability for agricultural use and potential impact on soil properties and plant growth. Among these parameters, Electrical conductivity (EC) represents the most widely used indicator of total dissolved salt concentration in water. Classification systems for irrigation water salinity have been established by various organizations. According to FAO guidelines, water with EC below 0.7 dS/m is considered to have no restriction on use, EC between 0.7-3.0 dS/m requires slight to moderate restrictions, and EC above 3.0 dS/m necessitates severe restrictions with special management practices. Surface irrigation water typically ranges from 0.3-0.6 dS/m, while groundwater in arid and semi-arid regions may vary from less than 1 dS/m to over 15 dS/m. Another critical parameter is Sodium Adsorption Ratio (SAR) that evaluates the relative proportion of sodium to calcium and magnesium ions in water, a high SAR values (above 3-6) can lead to soil structural degradation through clay dispersion, reduced infiltration rates, and formation of surface crusts, causing sodicity problems. Water pH affects nutrient availability and can influence the solubility of potentially toxic elements. Alkaline water (pH > 8.5) with high carbonate and bicarbonate concentrations can interfere with uptake of essential nutrients including calcium, magnesium, zinc, iron, and boron. Conversely, water with pH below 5 may be corrosive to irrigation infrastructure. The composition of irrigation water significantly influences its management requirements.

2.2 Mechanisms of Salt Stress in Plants

Salt stress imposes multifaceted constraints on plant growth and development through interconnected osmotic, ionic, and oxidative stress pathways that disrupt normal physiological processes and cellular homeostasis. Understanding these mechanisms is fundamental to developing effective management strategies for vegetable production under saline conditions. This mechanism involves Osmotic stress which represents the immediate and primary effect of soil salinity, occurring when the concentration of salts in the soil solution reduces the water potential, making water less available to plant roots. High external salt concentrations create a more negative osmotic potential in the soil compared to plant cells, restricting water uptake by roots

and leading to physiological drought despite the physical presence of water ^[2]. Similarly, Ionic stress which develops more gradually than osmotic stress, emerging over days to weeks as salt ions, particularly sodium (Na^+) and chloride (Cl^-), accumulate in plant tissues to toxic levels. Excessive Na^+ in the cytoplasm interferes with enzyme activity and protein function through competition with essential cations, particularly potassium (K^+), which is structurally like sodium but serves critical roles in enzyme activation, osmotic regulation, and stomatal function. The disruption of K^+/Na^+ homeostasis impairs numerous metabolic processes including photosynthesis, protein synthesis, and energy metabolism ^[1]. Nutrient imbalances occur under saline conditions as excessive Na^+ and Cl^- compete with and antagonize the uptake and utilization of essential macronutrients and micronutrients. The Na^+/K^+ antagonism is particularly significant, as Na^+ competes for K^+ binding sites on transporters and enzymes, disrupting crucial physiological processes. Calcium uptake may be inhibited by high Na^+ concentrations, compromising membrane stability and cell wall structure ^[3]. These nutritional disturbances compound the direct toxic effects of excessive salts, further limiting plant growth and productivity. Combining all these factors the plant growth is inhibited by using saline water.

3. Impact of Saline Water on Vegetable Crops

Vegetable crops exhibit a spectrum of physiological and biochemical responses when exposed to saline irrigation water, with the severity and nature of responses varying according to crop species, developmental stage, salinity level, duration of exposure, and environmental conditions. Understanding these responses is crucial for implementing appropriate management strategies and selecting suitable crops for saline environments ^[4]. Germination and seedling establishment is most salt-sensitive phases, high salinity in the germination medium reduces seed imbibition by lowering the osmotic potential of the surrounding solution, delaying, and reducing germination percentage. The inhibition of germination results from impaired water uptake, disrupted enzyme activity, and delayed or reduced mobilization of seed reserves necessary for embryo development ^[7]. In case of seedlings their growth is particularly vulnerable to salinity stress, with reductions in root length, shoot length, and biomass accumulation. Research on cucumber genotypes exposed to salt stress revealed significant reductions in plant height, leaf area, and dry biomass production. Root systems, which first encounter soil salinity, often exhibit more pronounced sensitivity than shoots, with decreased root elongation, reduced lateral root formation, and compromised root architecture affecting nutrient and water acquisition capacity. On later stage, Photosynthesis and carbon assimilation are profoundly affected by salinity through multiple mechanisms operating at different levels. Chlorophyll content typically declines under salt stress, contributing to chlorosis and reduced light harvesting efficiency. For example, Tomato plants irrigated with saline water exhibited decreased chlorophyll concentrations and reduced photosynthetic rates proportional to salinity levels ^[17]. As far as transpiration is concerned its rate generally decline under saline conditions due to stomatal closure and reduced leaf area, although this response helps conserve water and restrict ion uptake. The water use efficiency may increase moderately under mild

salt stress but typically decreases at higher salinity levels as photosynthesis is more severely affected than transpiration.

3.2 Salt Tolerance of Major Vegetable Crops

Factors influencing salt tolerance in vegetable crops include genetic background, developmental stage, environmental conditions (temperature, humidity, light intensity), irrigation method, soil type and drainage characteristics, and duration of salt exposure. Vegetable crops can be grouped based on their threshold EC values and sensitivity slopes. Vegetables crop ranges from highly sensitive (threshold EC < 1.5 dS/m) to moderately tolerant (threshold EC 3-4 dS/m), with relatively few species exhibiting high tolerance (threshold EC > 4 dS/m) include asparagus, beets, and certain cultivars of kale and spinach. Asparagus has been documented as the most salt-tolerant vegetable crop commercially available, capable of producing satisfactory yields even with irrigation water EC approaching 8-10 dS/m ^[5]. Spinach exhibits considerable variability in salt tolerance depending on cultivar and seasonal climate, with studies reporting threshold values ranging from 2-4 dS/m and it is important to note that spinach grown under cooler conditions demonstrates substantially greater tolerance than when cultivated in warmer climates ^[6].

3.3 Effects on Growth, Yield and Quality

The impacts of saline water irrigation on vegetable crop growth, yield, and quality parameters are multidimensional, affecting both quantitative production metrics and qualitative attributes that determine market value and nutritional content. Vegetative growth is consistently reduced under saline irrigation, with severity proportional to salinity levels and duration of exposure. Plant height, stem diameter, leaf number, leaf area, and total biomass accumulation decline as salinity increases beyond threshold values ^[11]. Field experiments with tomato in naturally ventilated polyhouses showed that yields were highest with freshwater irrigation but remained acceptable with saline water up to 10 dS/m when appropriate drip irrigation management was implemented, though 10 dS/m significantly reduced pepper and capsicum yields ^[10, 11]. Development of Root system is particularly sensitive to salinity, with reduced root length, altered root architecture, and decreased root biomass commonly observed. Not only root development but Flowering and fruit set can be delayed or reduced under saline conditions, affecting both the timing and magnitude of yields. Salt stress during reproductive stages may reduce pollen viability, impair fertilization, increase flower abortion, and decrease fruit set percentage. Research on tomato documented that salt stress applied at flowering stage significantly reduced fruit number per plant compared to stress applied during vegetative or fruit development stages ^[12]. As far as fruit quality is considered responses to salinity are complex, with some quality parameters improving while others deteriorate. Soluble solids content (°Brix), sugars, organic acids, vitamin C, and secondary metabolites including lycopene, phenolics, and flavonoids often increase under moderate salt stress, potentially enhancing flavour intensity and nutritional value. Nutritional composition is also influenced by salt stress in ways that may enhance or diminish vegetable value. Moderate salinity may increase concentrations of health-promoting phytochemicals including antioxidants, while maintaining or slightly increasing mineral content.

However, excessive salinity can negatively impact quality through effects including fruit size reduction, premature ripening, increased incidence of physiological disorders, reduced shelf life, and development of off-flavours.

4. Nematodes in the saline environment

Nematodes are the most numerous of all the multicellular organisms. Almost 500, 000 species of nematodes are known worldwide. They occur in every habitat which can support life. Nematodes depend on the water films around soil or organic material and move within existing pathways of soil pores of 25 to 100 µm diameter (Neher, 2020).

Salinity as well as nematodes, both is important in agriculture. Salinity affects the plant, which is a host to so many nematodes. The chemical composition of soil solution directly affects nematodes (Bird, 1977). A great deal of work has been done on salinity relations of plants. The influence of salts on nematode infectivity is not much clear. The hatching of eggs, parasitism and various developmental stages are likely to be affected by the salinity. The overall effects probably vary depending upon the combination of nematode, host, chemical causing salinity and level of salinity, linked with other factors in soil (Khan and Khan, 1990). The role of salinity in nematode-plant interaction has been partially studied in cotton (Heald and Heilman, 1971), tomato (Maggenti and Herdman, 1973), sweet orange (Van Gundy and Martin, 1961), Okra and brinjal (Jain *et al.*, 1989). Besides nematode ecology in natural saline and hyper-saline ecosystems which supports a huge number of free-living nematodes, this section of paper also briefly explores the effects of salinity on nematode survival, their hatching and behaviour and plant-nematode interaction.

4.1 Survival

The survival of nematode larvae may be influenced by various salts and ions. During dry and wet period, soil nematodes are subjected to variable salt concentration in the soil solution. The effect of different salts have not been recorded the same on the survival of different species of plant parasitic nematodes.

Ray and Das (1980) reported from India that many species of *Tylenchus*, *Tylenchorhynchus*, *Pratylenchus* and *Aphelenchoides* were tolerant to slightly saline soil conditions, while species like *Helicotylenchus dihystra*, *Hirschmanniella gracilis* and *Macroposthenia ornata* thrived well in moderately saline soil. A few other like *Rotylenchulus reniformis*, *Hemicriconemoides spheriocephala*, *Hemicriconemoides cocophillus* and *Caloosia exilis* tolerated strongly saline conditions. Among Dorylaims; *Xiphimema vulgare*, *X. elongatum*, *Paralongidorus citri* and a few species of *Dorlaimus* and *Tylencholaimus* were abundant in saline soil.

4.2 Movement and Behaviour

Movement and locomotion activities of animals are biologically necessary for migration, obtaining food, shelter from enemies; escape from adverse environmental conditions and also to locate a potential mate (Azmi and Jairajpuri, 1975). According to Jairajpuri *et al.* (1974) as concentration of salts solution increases, nematode first exhibit the jerky movements before finally becoming inactive. In 0.4M mercuric iodide solution the nematodes die immediately forming irregular bends with their cuticle showing many folds. At lower concentrations of salt

solutions the worms show increased activity as if irritated on being introduced to the solution. The movements take the form of lashing, spiraling, and forming figures of '8'. The bending of the body is more often combined with side-ways rolling either of the whole or part of the body. This activity seems similar to the observed by Stephenson (1945) for *Rhabditis* and Banage and Visser (1965) for *Dorylaimus*. *X. basiri* and *M. minor* usually showed the movements of the posterior part of the body and only occasionally of the anterior part especially when approaching death. However, *Haplolaimus indicus* and *Helicotylenchus indicus* continued to show movements of the entire body even when very near to death.

4.3 Hatching of Nematode Eggs

The hatching of eggs is affected by several environmental factors including temperature, soil moisture, soil aeration, pH, and organic or inorganic chemicals in the soil water. The chemicals may be derived from the soil itself or from organic matter or soil inhabiting micro-organisms (Shepherd and Clarke, 1971). According to Kanwar *et al.* (1989) when eggs of *M. javanica* were exposed to sodium hypochlorite at different concentrations, eggs showed less hatching at 750 and 1000 ppm than the control whereas the hatching was greater than the control at lower concentrations. Maqbool *et al.* (1987) used sodium chloride and calcium chloride separately and in combination and found that hatching of *M. javanica* eggs decreased with increasing concentration. At all salt concentrations the number of emerged juveniles after 24, 48 and 72 hours were greater in sodium chloride treatment. Calcium chloride and Sodium chloride + Calcium chloride were more detrimental to the hatching of eggs. Juvenile infectivity was inversely proportional to the salt concentration. Up to 7 days juvenile penetration to tomato roots was relatively more in Sodium chloride than in calcium chloride or in combination of the two salts. Similar observations were made by Khan and Khan (1990) who tested various concentrations of sodium chloride and sodium bicarbonate and found that all the levels of salinity inhibited the hatching of *M. javanica* and *M. incognita* eggs and reduced their mobility. A negative correlation between hatching and salinity levels was recorded.

4.4 Role of Soil Salinity in Plant-Nematode Interactions

Heald and Heilman (1971) found that nematodes intended plants at high salinity levels dropped several bottom leaves and plants were very weak with thin stems. The reniform nematode attacks and damages cotton plants at all salinity levels, and nematode injury increases with soil salinity. Salinity interacts with biotic pests and diseases including root rot (*Phytophthora* spp.), nematodes and mycorrhizae. Irrigation with high salinity water not only can have direct effects on root pathogens but it can also predispose citrus root stocks to attack by root rot and nematodes. Nematodes and mycorrhiza can affect the salt tolerance of citrus roots and may increase Chloride ion uptake. Not all effects of salinity are negative; as moderate salinity stress can reduce physiological activity and growth, allowing citrus seedlings to survive cold stress and can even enhance flowering after the salinity stress relieved (Sylvetsen and Levy (2005). Edongali and Ferris (1981) showed that the presence of salt resulted in higher infectivity on tomato by *Meloidogyne* species. Maximum infectivity was obtained by sodium chloride treated juveniles from all egg sources.

Nematodes in our agricultural systems have been the center of our interest for quite some years. The characteristics of nematofauna and its ecology in various natural ecological systems of India is, however, a neglected issue of research. Our diverse ecosystems-ice-laden areas in the North, arid plains and dunes, brooks, streams, rivers and their deltas and estuaries, Sea channels and mangroves, all are almost virgin areas of research in this respect. Essential research is needed on nematodes in natural and agricultural systems for disease suppression, for understanding and restoration of the environment and construction of better predictive models for land use decisions.

5. Management Strategies for Saline Water Irrigation

The selection and management of appropriate irrigation systems represent cornerstone strategies for successfully utilizing saline water in vegetable production. Surface irrigation methods including furrow and basin flooding are generally less suitable for saline water application due to non-uniform water distribution, high evaporation losses, and difficulty controlling leaching. Different irrigation methods vary substantially in their capacity to control salinity accumulation and maintain productive growing conditions. One of the effective irrigation methods is drip irrigation which is widely recommended technology for saline water application in vegetable crops^[8]. In this method water is directly applied to the root zone through a network of tubes and emitters, offering multiple advantages for salinity management. Frequent, small irrigation applications maintain relatively constant soil moisture and prevent salt concentration in the root zone that would occur with less frequent, heavy irrigations^[16]. High-frequency drip irrigation creates a salt-free or low-salt zone around each emitter where root proliferation is encouraged^[9]. Studies comparing drip irrigation to furrow irrigation for tomato cultivation under saline conditions demonstrated that drip systems maintained lower root zone salinity, improved water distribution uniformity, and achieved higher yields^[17, 18]. The better performance of drip irrigation results from reduced surface evaporation, minimal wetting of foliage, precise water delivery matching crop requirements, and facilitation of leaching when excess water is applied and in case of Subsurface drip irrigation (SDI), where drip lines are buried below the soil surface, offers additional advantages for salinity management including reduced surface evaporation and prevention of surface salt crusting.^[4] However, SDI systems require careful management because salts can accumulate at the soil surface above buried drip lines, potentially inhibiting germination of direct-seeded crops. Strategies to address this challenge include supplemental sprinkler irrigation for germination, transplanting seedlings, bed shaping to allow planting in zones of lower salinity, or periodic surface leaching events. Another irrigation method is sprinkler irrigation which can be effective for salinity management during certain growth stages, particularly for leaching accumulated salts or establishing crops in fields managed with SDI. However, sprinkler application of highly saline water can damage sensitive crops through direct foliar contact with salts, causing leaf burn and reduced photosynthetic capacity. Other irrigation strategies are Regulated deficit irrigation (RDI) strategies it involves deliberate application of water below full crop requirements during specific growth stages that are less sensitive to water stress, while maintaining

adequate irrigation during critical periods. When combined with saline water, RDI reduces total salt loading to the field while potentially improving water productivity. Research on apples demonstrated that RDI reduced water use by 20% and decreased soil salinity compared to full irrigation. Similarly, Partial root-zone drying (PRD), an RDI variant where alternate sides of the root system are irrigated in successive events, this technique triggers hormonal signals that promote water use efficiency while reducing total water and salt application. Studies on sunflower demonstrated that alternating fresh and saline water application using PRD maintained yields while reducing salt accumulation.

Strategic blending of saline and fresh water or cyclic alternation between water sources of different qualities offers practical approaches to extend limited freshwater supplies while managing salinity impacts on crop production. Water blending involves mixing saline water with freshwater prior to application, achieving intermediate salinity levels more suitable for crop production than undiluted saline water. The proportion of fresh to saline water in blends can be adjusted based on crop salt tolerance, growth stage, and availability of each water source [19]. Experiments comparing blending versus sequential application of fresh and saline waters found that blending generally provided more uniform salinity conditions and better crop performance for some species. However, the effectiveness of blending depends on the specific ion composition of saline water sources; waters with high sodium chloride require different blending ratios than those dominated by calcium and magnesium salts. Another method for strategic blending is alternate irrigation which involves rotating between fresh and saline water applications rather than continuous blending, offering several advantages including reduced infrastructure requirements for mixing and flexibility to adjust water quality based on crop needs at different growth stages [20]. This approach can be implemented at different temporal scales, from alternating each irrigation event to seasonal rotations. A critical consideration in cyclic strategies is the temporal dynamics of salt accumulation and leaching, which vary with soil type, climate, and crop water use patterns. Light-textured soils with rapid infiltration enable more frequent alternation and effective leaching, while heavy clay soils require longer intervals between saline irrigations to prevent buildup [19]. Arid climates with high evapotranspiration demand more frequent fresh water applications compared to semi-arid regions with moderate evaporation.

6. Conclusion

The growing scarcity of freshwater resources is compelling agriculture, particularly in arid and semi-arid regions, to seek alternative water sources for crop production. Saline water irrigation, despite its potential to cause osmotic stress and ion toxicity, can be effectively utilized through carefully managed practices. Selection of salt-tolerant vegetable species and cultivars is crucial to optimizing crop performance under saline conditions.

Advancements in agronomic techniques—including regulated deficit irrigation, blending of saline and freshwater, fertigation, and the use of soil amendments—have demonstrated success in reducing the adverse effects of salinity. The adoption of salt-tolerant rootstocks, halophyte crops, and plant growth-promoting rhizobacteria further

strengthens crop resilience. Technological innovations such as drip irrigation, remote sensing, and precise salinity monitoring support efficient water use and reduce salt accumulation in the root zone.

Sustained use of saline water requires integrated management and ongoing evaluation to protect soil health and maintain environmental sustainability. Future research should prioritize breeding for enhanced salt tolerance, investigating plant-microbe interactions under saline stress, and developing cost-effective desalination or water blending solutions. With appropriate management, saline water can serve as a valuable resource, advancing sustainable vegetable production and contributing to global food security amidst increasing water scarcity.

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