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Review

Growth and Phytoremediation Potential of *Salicornia* spp. Under Different Wastewater Irrigation Regimes: A Review

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Abstract

Salicornia is a genus of salt-tolerant plants capable of growing and producing biomass under conditions that severely constrain conventional agriculture. Beyond its ecological niche as a halophyte, *Salicornia* has emerged as a multifunctional crop for sustainable food, feed, and bio-based production in saline landscapes. The increasing generation of saline wastewaters and brines from aquaculture, municipal treatment, agro-industrial activities, and greenhouse systems intensifies the need for natural solutions that can recover resources while protecting soils and receiving ecosystems. This review synthesizes current understanding of how *Salicornia* species perform when irrigated with saline wastewaters, with particular attention to their dual role as productive crops and phytoremediation agents. It further examines the biological mechanisms underlying salt tolerance and the influence of wastewater characteristics on biomass production and phytoremediation performance. Overall, the evidence indicates that *Salicornia* performs particularly well in nutrient-rich, controlled saline effluents, whereas more complex wastewater matrices require careful contaminant management to ensure biomass quality and safe reuse. This synthesis positions *Salicornia* as a fundamental species for circular and climate-resilient strategies linking saline wastewater reuse with crop production, while emphasizing that standardized reporting, long-term field validation, and contaminant-aware biomass management remain essential to support wider adoption.

Keywords: halophytes; saline wastewater; circular bioeconomy; agronomic performance; phytoremediation

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1. Introduction

Global freshwater resources are declining at an accelerating rate, with terrestrial water storage decreasing by approximately 1200 km^3 since 2014, and soil salinisation now affecting over one billion hectares of agricultural land worldwide, threatening food security and ecosystem stability [1,2]. At the same time, wastewater streams from aquaculture, municipal systems, olive mill wastewater, and desalination are increasing in volume and chemical complexity [3,4], encompassing saline effluents and brines [3], as well as high-organic-load wastewaters rich in nutrients, phenolic compounds, and other phytotoxic constituents [5,6]. Aquaculture production alone reached 94.6 million tonnes in 2018,

generating nutrient-rich effluents, whereas olive mill wastewater may reach chemical oxygen demand (COD) concentrations up to 200,000 mg L^{-1} [5,7,8]. These converging pressures expose a structural limitation in current water management systems, particularly in coastal, arid and saline regions where freshwater scarcity and salt accumulation intersect.

Conventional wastewater treatment technologies are largely optimised for freshwater matrices and perform suboptimally under saline conditions. Elevated salt concentrations inhibit microbial metabolism in biological treatment units, disrupt nitrification and denitrification pathways, and impair floc stability [9]. Although physical and chemical treatments can remove pollutants, they are energy-intensive and economically restrictive, limiting scalability in developing regions [5]. Consequently, cost-effective, natural-based solutions capable of operating under high salinity while enabling nutrient recovery have become a priority in sustainable water governance [10]. Although wastewater reuse in agriculture is increasingly recognised as a strategy to conserve freshwater and recycle nutrients, more than 80% of global wastewater remains untreated [4]. While treated effluents can supply nitrogen and phosphorus and reduce fertiliser inputs [11], risks of heavy-metal accumulation, pathogen transfer and organic contaminants require careful species selection and system design [11].

Halophytic crops provide a promising biological interface for both saline wastewater treatment and biomass production. Among them, *Salicornia* species have emerged as model systems due to their obligate halophytism, global distribution across coastal marshes and inland saline flats, as well as their capacity to thrive under high electrical conductivity and fluctuating ionic regimes [2,12,13]. Their agronomic potential spans fresh vegetable markets, oil-rich seeds containing up to 30% lipids suitable for biofuel feedstocks and biomass enriched in bioactive compounds [14,15]. Growth is often stimulated at moderate salinity with optimal performance reported between 200–400 mM NaCl and tolerance exceeding 1000 mM in certain taxa, although thresholds vary by species [14,16,17]. These characteristics position *Salicornia* as a candidate crop capable of converting saline and marginal resources into economic outputs while contributing to environmental remediation.

The functional basis of this resilience lies in coordinated morphological, physiological and rhizosphere-mediated mechanisms. Tissue succulence, vacuolar Na^+ sequestration and Na^+/H^+ antiporter activity maintains cytosolic ion homeostasis under hypersaline exposure [18–20]. Compatible solutes such as proline and glycine betaine stabilise proteins and membranes, while antioxidant systems mitigate oxidative damage induced by osmotic and ionic stress [21]. These plant-level processes interact with wastewater chemistry, where elevated ammonium and phosphorus loads can stimulate growth but require balanced management. In parallel, rhizosphere microbial communities contribute to nutrient assimilation and stress mitigation, thereby enhancing resilience under saline irrigation [22]. Constructed wetlands and hydroponic systems integrating *Salicornia* have reported nitrogen and phosphorus removal efficiencies exceeding 70% under controlled hydraulic regimes, particularly in aquaculture-derived effluents [22–25]. Nevertheless, more complex wastewaters introduce additional constraints. Olive mill effluents are characterised by high organic and phenolic loads [8], and municipal wastewater irrigation has demonstrated heavy-metal accumulation patterns in plant tissues [26]. Emerging contaminants, including pharmaceuticals, may also be absorbed and translocated [27]. Valorisation pathways, whether food, feed, biofuel or biorefinery applications, therefore, require contaminant-aware routing aligned with system chemistry [15,28].

Despite expanding experimental evidence, substantial gaps remain. Many studies are short-term or laboratory-based, limiting understanding of seasonal variability, long-term salinity accumulation and substrate saturation [29]. The relative contributions of plant uptake versus microbial transformation remain insufficiently quantified [30], and

multi-year assessments of contaminant fate and biomass safety are scarce [25,31]. Techno-economic and life-cycle evaluations are also limited [10,28]. Addressing these gaps requires integrative frameworks that connect physiological tolerance, hydraulic design, contaminant monitoring and circular bioeconomy deployment strategies. Unlike previous reviews that have primarily focused on individual aspects of *Salicornia* biology, saline agriculture, or phytoremediation, this review adopts a holistic approach by integrating plant physiology, wastewater characteristics, cultivation systems, biomass safety, and valorisation within the context of saline wastewater reuse.

This review synthesises current evidence on the growth performance and phytoremediation capability of *Salicornia* species under diverse saline wastewater irrigation regimes. Specifically, it (i) identifies the principal drivers including species selection, wastewater chemistry and system configuration that govern remediation efficiency and biomass yield; (ii) evaluates environmental and safety constraints associated with contaminant accumulation and valorisation pathways; and (iii) proposes research and design priorities to advance *Salicornia*-based systems as scalable, circular, and climate-resilient solutions for saline wastewater reuse.

2. Materials and Methods

Using Google Scholar, Scopus, Web of Science, and ScienceDirect, we conducted a literature search on *Salicornia* growth performance, stress physiology, phytoremediation capacity, wastewater chemistry, cultivation systems, and biomass valorisation under saline irrigation and wastewater-related conditions. The literature search focused primarily on publications from the last 10 years, while older studies were included when they provided essential background, foundational mechanisms, or key evidence relevant to the narrative synthesis. Peer-reviewed journal articles, review papers, books, technical reports, and selected institutional documents were considered if they directly addressed *Salicornia* cultivation, saline wastewater reuse, contaminant removal, wastewater chemistry, or biomass valorisation. Studies were screened manually by title, abstract, and full text, and were excluded if they were not directly relevant to *Salicornia* or saline wastewater systems, duplicated previously identified records, or lacked sufficient methodological detail or relevant outcome data to contribute meaningfully to the objectives of this review. Ninety-five relevant sources were retained and organised into thematic categories reflecting the structure of the review.

3. Biology and Stress Physiology of *Salicornia* Relevant to Wastewater Irrigation

3.1. Taxonomy and Species Distribution

The genus *Salicornia* (Amaranthaceae) comprises approximately 64 accepted species of obligate halophytes distributed across coastal salt marshes, estuaries, and inland saline flats worldwide [32,33]. This genus is characterized by a highly complex taxonomy, reflecting reduced morphological differentiation among species and pronounced phenotypic plasticity driven by steep salinity gradients and hydrological variability [32]. Their ecological versatility under fluctuating tidal and saline conditions provides the evolutionary foundation for their tolerance of high ionic-strength environments. Within this diversity, several species have emerged as reference taxa in saline agriculture and wastewater research, including *Salicornia europaea*, *Salicornia bigelovii*, *Salicornia brachiata*, and *Salicornia fruticosa* [21,33,34]. Recent phylogenetic studies indicate that *Sarcocornia* is nested within *Salicornia*, leading recent taxonomic treatments to include *Sarcocornia* within *Salicornia* [35]. However, because many ecological and applied studies continue to use the traditional *Sarcocornia* nomencla-

ture, both names are retained in this review where appropriate for clarity and consistency with the cited literature [36].

3.2. Morphological and Physiological Salt Tolerance Traits

The salt tolerance trait of *Salicornia* results from integrated physiological regulation and ion homeostasis mechanisms that maintain water balance and metabolic stability under elevated salinity [21,37,38]. Morphologically, *Salicornia* species are characterized by having succulent articulated photosynthetic stems and highly reduced leaves; these structural traits minimise transpiration while accommodating internal salt accumulation. A defining anatomical feature is pronounced tissue succulence, which increases the proportion of water-storage parenchyma and dilutes accumulated salts, thereby buffering osmotic stress. These structural adaptations are suitable for the fluctuating salinity and ionic complexity characteristic of saline wastewater irrigation regimes [21].

At the cellular level, ion compartmentalisation is central to tolerance. Vacuolar sequestration of Na^+ and Cl^- is mediated by tonoplast-localised Na^+/H^+ antiporters (NHX), energised by vacuolar H^+-ATPase and H^+-pyrophosphatase (V-PPase), which collectively preserve cytosolic ion homeostasis and enzymatic function [37,39,40]. Long-distance sodium transport is further coordinated through the Salt Overly Sensitive (SOS) signaling pathway, helping regulate Na^+ distribution between roots and shoots under saline conditions [38]. Structural plasticity further complements these transport processes. These coordinated structural and physiological mechanisms collectively maintain ion homeostasis, sustain plant growth, and enable *Salicornia* to tolerate the fluctuating salinity conditions characteristic of saline wastewater irrigation systems [33,41].

3.3. Osmolyte Accumulation and Antioxidant Responses

In addition to regulating inorganic ions, *Salicornia* species employ compatible solutes to achieve osmotic adjustment. Glycine betaine and proline accumulate under saline conditions and function in stabilising proteins, membranes, and enzymatic complexes while sustaining water uptake [37,42]. Salinity and wastewater-derived co-stressors, including elevated nutrient loads, phenolic compounds, and trace metals, promote the formation of reactive oxygen species (ROS). *Salicornia* mitigates oxidative stress through antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), peroxidases (POD), and glutathione S-transferases (GSTs), thereby preserving photosynthetic performance and membrane integrity under saline wastewater conditions [42–44]. The integration of osmolyte accumulation and antioxidant regulation enables tolerance to both osmotic stress and the oxidative complexity characteristic of saline wastewater matrices.

3.4. Rhizosphere Microbiome and Endophytes

The resilience of *Salicornia* extends beyond the physiological adaptations of the plant to include processes occurring in its rhizosphere. In saline environments, rhizosphere microbial consortia contribute to nutrient transformation, organic matter attenuation, and metal immobilisation through coupled nitrification–denitrification pathways and biofilm formation [45,46]. Root exudation and radial oxygen loss modify rhizosphere redox conditions, creating microsites that sustain microbial metabolic activity even under elevated salinity. Plant growth-promoting rhizobacteria (PGPR) associated with halophytes enhance nutrient acquisition, modulate phytohormone signaling, and reinforce stress tolerance pathways [45]. Plant ion homeostasis is closely linked with rhizosphere dynamics under saline conditions, further contributing to the functional stability of *Salicornia*-based treatment systems [47]. These plant–microbe interactions provide a basis for their functional

stability in saline treatment environments and highlight opportunities to optimise the microbiome in wastewater systems.

3.5. Relevance to Wastewater Irrigation Regimes

Collectively, the anatomical and physiological traits of *Salicornia* establish a foundation for its application under saline wastewater irrigation regimes [21,37]. Ion compartmentation and regulated ion transport buffer elevated electrical conductivity and complex ionic compositions. Osmolyte accumulation and antioxidant systems confer tolerance to osmotic fluctuations and oxidative co-stress associated with nutrient-rich or organically loaded effluents [17]. Concurrently, rhizosphere processes facilitate the transformation and stabilisation of nitrogen, phosphorus, organic matter, and trace metals within saline matrices. This integration of physiological adaptation, whole-plant function, and rhizosphere processes enables stable plant performance under variable hydraulic loading rates and retention times typical of engineered saline wastewater systems [48]. These biological properties underpin subsequent analyses of biomass production, phytoremediation performance, and system design considerations presented in later sections, positioning *Salicornia* as a key candidate for the reuse of saline wastewater within circular bioeconomy frameworks. Accordingly, this section focuses on the principal physiological mechanisms that directly influence plant establishment, biomass production, contaminant tolerance, and phytoremediation performance under saline wastewater irrigation. The interactions between *Salicornia* response mechanisms, saline wastewater stressors, rhizosphere processes, and engineering controls are summarised in Figure 1.



Figure 1. Conceptual framework outlining *Salicornia* response mechanisms with saline wastewater stressors, rhizosphere processes, and engineering controls influencing treatment outcomes in saline wastewater systems. Nano Banana (Google Gemini image-generation model) was used for figure generation.

4. Wastewater Types and Chemistry Used in *Salicornia* Studies

Saline wastewaters studied in *Salicornia* research span a wide chemical spectrum, differing in ionic composition, salinity intensity, nutrient regime, organic load, and co-occurring contaminants. These matrices range from nutrient-enriched marine effluents to hypersaline agro-industrial brines, each imposing a distinct chemical context on the plant-substrate system [21,33,46]. Understanding the chemistry of these influents is essential

before evaluating agronomic performance or remediation efficiency, as their composition ultimately determines both stress intensity and resource availability.

4.1. Aquaculture and Integrated Multi-Trophic Aquaculture (IMTA)-Linked Effluents

Marine and brackish aquaculture effluents from land-based fish and shrimp farms, including recirculating aquaculture systems (RAS) and integrated multi-trophic aquaculture (IMTA), represent one of the most frequently studied wastewater types for *Salicornia* cultivation [24,25,49–52]. Chemically, these effluents resemble seawater enriched with dissolved nutrients. Salinity levels are typically comparable to marine conditions, while nitrogen and phosphorus concentrations are increased due to feed inputs and excreted wastes [24,50]. In intensive RAS systems, nitrate commonly reaches several tens of mg N L^{-1} [24,25] and phosphate is frequently reported between 0.5 and 5 mg P L^{-1} [25,26,50,51]. Dissolved and particulate organic matter derived from uneaten feed and faecal material [49,50] contributes to chemical oxygen demand (COD), generally ranging from several tens [25] to a few hundred mg L^{-1} after solids removal [31].

This combination of seawater-level salinity and bioavailable nutrients creates a matrix that closely mirrors the natural habitats of many halophytes [21]. In this context, salinity does not act as an isolated stressor but as a background condition within which nutrient enrichment becomes the defining chemical feature [33]. Aquaculture effluents, therefore, provide a chemically consistent and relatively stable environment for evaluating saline nutrient recovery systems.

4.2. Greenhouse Drainage and Hydroponic Recirculation Waters

These greenhouse drainage waters and recirculating hydroponic solutions originate from soilless cultivation systems in which nutrient solutions are partially reused and periodically discharged [25,53]. Unlike aquaculture effluents, their chemical profile is composed primarily of fertilisers rather than by-products derived from animal metabolism.

Electrical conductivity for these effluents typically ranges between 5 and 15 dS m^{-1}, reflecting salt accumulation during nutrient recycling [25,53] and aligning with established brackish water classifications [54]. These waters are characterised by elevated concentrations of plant-available nutrients; nitrate levels frequently reach 50–200 mg N L^{-1}, and phosphate is commonly observed between 5 and 30 mg P L^{-1} [25,53]. Organic loads are generally lower than in agro-industrial brines as the matrix is dominated by mineral fertiliser residues rather than recalcitrant organic compounds [55,56].

The chemical distinction between aquaculture and greenhouse effluents lies primarily in the origin of nutrients and the organic complexity of the effluents. While both may share moderate to high salinity, greenhouse drainage waters represent a nutrient-dense yet comparatively simpler matrix, in which ionic imbalance and nutrient accumulation are the principal chemical drivers [25,53].

4.3. Municipal and Domestic Wastewaters

Municipal and domestic wastewaters used in *Salicornia* studies primarily include secondary- or tertiary-treated sewage and landfill leachates [31,51]. Their chemical profile reflects the combined influence of household discharge, treatment efficiency, and local water salinity [46]. In experimental studies, secondary- or tertiary-treated municipal sewage effluents used for irrigation have been reported to contain approximately 32 mg L^{-1} total nitrogen and 0.5 mg L^{-1} phosphorus [31]. These treated effluents generally exhibit relatively low organic loads. By contrast, Chemical Oxygen Demand (COD) values of up to 550 mg L^{-1} refer to the initial composition of untreated or insufficiently treated municipal wastewater prior to irrigation rather than to the treated wastewater typically applied in *Salicornia* cultivation studies [31]. Therefore, the organic load experienced by *Salicornia* depends on the degree of wastewater treatment before reuse. In coastal or saline-influenced

regions, Total Dissolved Solids (TDS) typically range between 1000 and 10,000 mg L^{-1}, aligning with established brackish water classifications [54].

Beyond bulk nutrients and salts, these effluents carry heavy metals and pharmaceutical residues, adding a layer of chemical complexity [26,57]. Field observations demonstrate that *S. europaea* irrigated with municipal wastewater effectively accumulates Zn, Cu, Cd, Pb, and Ni while maintaining shoot biomass [26]. Controlled uptake studies further show that pharmaceutical compounds, including antibiotics and other persistent molecules, can be detected in root and shoot tissues following exposure [57]. Thus, the chemical profile of municipal effluents is defined not only by salinity and nutrients but also by the matrix heterogeneity increase caused by persistent co-contaminants.

4.4. Industrial and Agro-Industrial Brines

Industrial and agro-industrial saline wastewaters occupy the most chemically extreme end of the spectrum examined in *Salicornia* research. Among these, olive mill wastewater (OMWW) is prominent due to its exceptionally high organic load, with COD values frequently exceeding 200 g L^{-1} [56,58]. These streams are further characterised by phenolic concentrations reaching up to 17.5 g L^{-1} [55]. National-scale pollution assessments confirm the magnitude of these loads and highlight the limited biodegradability (reflected in a COD/BOD_5 ratio of ~2.6), distinguishing it as a high-intensity chemical environment compared to nutrient-enriched aquaculture effluents [58]. More broadly, saline industrial wastewaters, including those from the tannery and petrochemical sectors, carry distinct contaminants such as heavy metals (Cr, Pb, Hg) and aromatic compounds [59,60]. In these matrices, salinity interacts with compound-specific toxicity, creating a remedial context that differs fundamentally from simple nutrient-driven systems.

4.5. Desalination Brines

Desalination processes generate concentrated brines characterised by elevated dissolved solids and residual process additives [54]. These reject streams represent a distinct class of saline wastewater increasingly considered for circular-economy applications involving halophyte cultivation [54,61].

Desalination brines are defined primarily by high total dissolved solids and stable major-ion composition [54]. Unlike aquaculture or greenhouse drainage waters, they are typically nutrient-poor unless blended with other streams [61]. In addition, process-related chemicals such as antiscalants or biocides may be present, adding an anthropogenic chemical component to the salinity background [54]. Integrated reuse systems combining desalination concentrate with aquaculture or crop production demonstrate how such brines can be repositioned within managed production systems [62].

4.6. Synthetic Saline Media and Experimental Salinity Gradients

Synthetic saline media, commonly prepared by adding NaCl to nutrient solutions, are widely used to define physiological response curves under controlled salinity gradients [17]. These systems span concentrations from 10 to 500 mM NaCl and enable the isolation of osmotic and ionic stress in the absence of complex organic or contaminant matrices.

Optimal growth for several *Salicornia* species is frequently reported around 200–300 mM NaCl, with performance declining outside this range depending on species and ecotype [17,42]. These experiments provide a reference frame for interpreting real wastewater conditions, where salinity interacts with nutrient availability, organic matter, and co-contaminants. Across these wastewater classes, a clear gradient in matrix complexity becomes evident, ranging from nutrient-rich and relatively stable effluents (aquaculture and greenhouse systems) to increasingly heterogeneous and contaminant-driven matrices (municipal and agro-industrial wastewaters), and finally to ion-dominated but nutrient-limited concentrates

(desalination brines). This progression defines the environmental context within which *Salicornia*-based systems operate. The following sections examine how differences in matrix complexity translate into biomass performance, contaminant partitioning, and treatment functionality under saline irrigation regimes.

5. Agronomic Performance of *Salicornia* Under Real Wastewater Irrigation Regimes

Agronomic performance data under real saline wastewaters come primarily from (i) marine recirculating aquaculture and IMTA-linked effluents, including saltwater aquaponics, (ii) constructed wetlands or nutrient-recovery beds treating saline aquaculture discharges, (iii) controlled hydroponics exposed to saline effluents or industrially influenced waters, and (iv) seawater-based irrigation in saline soils, sometimes amended to improve fertility [24,63–66]. Across these platforms, the strongest agronomic inference is produced where studies report (a) influent chemistry beyond EC (major ions and N form at minimum), (b) planting density and harvest definition, and (c) biomass as dry weight or paired FW and DW [21,46,67].

Cross-study synthesis remains constrained by gaps recurring in reporting practices that are disproportionately consequential for a highly succulent crop. Many studies present fresh biomass without concurrent dry-weight conversion, omit density or harvest schedule (preventing areal productivity normalization), or report EC without nutrient speciation and co-stressor screening (COD/phenolics, metals, pharmaceuticals) [21,46,67]. Because tissue water fraction, ash, and ion partitioning in *Salicornia* shift with salinity and developmental stage, FW-only comparisons collapse physiological response and management effects into a single ambiguous metric [21,67].

Based on the reporting limitations identified in the reviewed literature, future investigations of *Salicornia* cultivated under saline wastewater irrigation should adopt a minimum reporting framework to improve comparability and reproducibility across studies. At a minimum, this framework should include: (i) biomass yield as dry weight (DW), with fresh weight (FW) provided only as complementary information; (ii) planting density (plants m^{-2}), together with harvest timing and frequency, to enable meaningful areal productivity comparisons; and (iii) the complete elemental composition of harvested biomass, particularly Na, K, Cl, and potentially toxic elements (e.g., Cd, Pb, Zn, Cu, and Ni), to support agronomic evaluation, biomass valorisation, and food or feed safety assessments. In addition, comprehensive characterization of wastewater chemistry, including nutrient speciation and relevant co-contaminants, should accompany these parameters to facilitate robust cross-study comparisons and strengthen future meta-analyses.

Interpretation of wastewater performance therefore requires an agronomic baseline derived from optimized saline cultivation systems. Ventura et al. [68] showed that seawater-irrigated *Salicornia* can produce cumulative fresh biomass above 8 kg FW m^{-2} over a 10–12 week cycle, with a 3-week harvest interval outperforming shorter or longer cutting regimes and annual ecotypes outyielding perennial *Sarcocornia* types. In hydroponics, Hulkko et al. [15] reported that *S. europaea* produced 1586 g total fresh biomass at 0 mM NaCl and 4365 g at 342 mM NaCl, identifying 342 mM NaCl as the growth optimum and confirming that non-saline conditions substantially suppress biomass formation. Cárdenas-Pérez et al. [32] similarly observed that intermediate salinity levels promoted greater shoot development, succulence, and vegetative biomass than low-salinity treatments, reinforcing the requirement of saline conditions for optimal growth. Ventura and Sagi [21] further established the conceptual basis for treating *Salicornia* as a halophytic crop within seawater-based agricultural systems. Under field conditions, El-Nwehy et al. [69] demonstrated that managed dilution and fertilization substantially improved productivity, with the best

irrigation treatment producing 2781 g m^{-2} fresh biomass, 1328 g m^{-2} dry biomass, and 286 g m^{-2} seed yield, while the best combined irrigation and fertilization treatment increased productivity to 3218 g m^{-2} fresh biomass, 1576 g m^{-2} dry biomass, and 413 g m^{-2} seed yield. Complementarily, Al-Tamimi et al. [70] demonstrated that productivity under saline irrigation is also strongly dependent on hydraulic management and salt balance, with aquabrine-irrigated *Salicornia bigelovii* producing 649 g m^{-2} fresh tips under leaching fractions ranging from 0.30 to 0.74 depending on irrigation design. Within this agronomic framework, wastewater-irrigated systems should be interpreted against managed saline cultivation benchmarks rather than freshwater crop standards, because productive *Salicornia* cultivation depends on the interaction between salinity, nutrient availability, harvest regime, and root-zone salt management [15,21,32,68–70].

5.1. Biomass Yield and Growth Stability by Wastewater Class

Across wastewater classes, yield outcomes are best interpreted as two overlapping envelopes rather than a single "salt tolerance" narrative, as summarized in Table 1. In nutrient-sufficient saline streams (aquaculture/IMTA effluents and many greenhouse recirculates), *Salicornia* often sustains vegetative growth across repeated harvests, with salinity primarily altering tissue composition and water content rather than eliminating productivity [21,25,71]. In streams with a complex chemical profile (industrial/agro-industrial brines and some municipal matrices), growth trajectories are more sensitive to co-toxicity, nutrient imbalance, and matrix effects, shifting feasibility toward dilution, pretreatment, or conditional biomass routing [46,55,65].

Where dry biomass is reported under nutrient-sufficient saline irrigation or hydroponics, yields commonly fall on the order of ~1–4 kg DW m^{-2} per crop cycle, but direct comparison is frequently limited by differences in density, harvest frequency, and inconsistent FW:DW reporting [21,25,71–73]. Consequently, "high yield" in this literature is often operationally defined by sustained regrowth and stable marketable fraction under a specified regime, rather than by a single absolute biomass number [66,74,75].

5.1.1. Aquaculture and IMTA-Linked Effluents

Aquaculture and IMTA-linked effluents provide the strongest evidence that saline wastewater can sustain high glasswort productivity when nutrient supply is sufficiently abundant and compositionally balanced [24,76]. In a 74-day artificial wetland study, *Sarcocornia neei* produced 11.3 ± 2.0 kg FW m^{-2} under mixed NH_4^+ + NO_3^- nutrition and 10.0 ± 0.8 kg FW m^{-2} under NO_3^- supply, compared with 4.6 ± 0.6 kg FW m^{-2} in the unfertilized control, corresponding to biomass increases of 146% and 117%, respectively, relative to the control [24]. Although this study used *S. neei* rather than *Salicornia europaea*, it remains a relevant glasswort comparator because its productivity exceeded the seawater-irrigated *Salicornia* benchmark introduced in Section 5, where cumulative yields above 8 kg FW m^{-2} over 10–12 weeks represent highly productive saline cultivation [24,68].

Direct evidence in *S. europaea* confirms that nitrogen form is a major agronomic control on biomass accumulation in aquaculture-linked systems. Under nutrient conditions designed to simulate aquaculture wastewater, final plant biomass was lowest under NH_4^+ supply at approximately 0.25 g DW $plant^{-1}$, increased to about 0.35 g DW $plant^{-1}$ under NO_3^-, and reached about 0.47–0.48 g DW $plant^{-1}$ under mixed NH_4NO_3, indicating that the mixed-N treatment produced roughly 90% more biomass than ammonium alone and about 35–40% more than nitrate alone [76]. This biomass response was accompanied by improved plant N status: tissue N concentration increased from 8.6 ± 1.2 mmol N g^{-1} DW under NH_4^+ to 10.1 ± 1.6 and 10.4 ± 1.3 mmol N g^{-1} DW under NO_3^- and NH_4NO_3, respectively, while total N per plant increased from 0.4 ± 0.1 to 0.6 ± 0.3 and

0.6 ± 0.2 mmol N plant^{-1} [76]. The same study also showed a shift in biomass partitioning, with shoot:root ratios rising from 2.1 ± 0.07 under NH_4^+ to 2.6 ± 0.06 under NO_3^- and 2.8 ± 0.05 under NH_4NO_3, confirming that nitrate-containing nutrition supported greater aboveground development than ammonium alone [76].

A greenhouse aquaponic/RAS production study illustrates the lower-yield end of this wastewater class when nutrient balance is inadequate. In that system, total harvested *Salicornia* biomass reached 9.25 kg per cycle, equivalent to approximately 0.58 kg m^{-2}, which was about 12-fold lower than the fertilizer-supplied control [77]. The crop still completed growth, but vegetative productivity was strongly reduced and the plants shifted earlier toward flowering and lignification, which reduced the marketable shoot fraction [77]. Long-term RAS studies further indicate that yield stability in aquaculture-linked systems depends not only on nutrient supply but also on hydraulic management, because *Salicornia virginica* was experimentally evaluated as a biomitigation crop for dissolved nutrients in marine finfish RAS effluent under controlled exchange conditions, highlighting the importance of water exchange and salt management for sustained plant performance [66].

Taken together, these studies show that aquaculture and IMTA-linked effluents can support either benchmark-level biomass or much lower yields depending on nutritional completeness and system management. Under nutrient-enriched marine effluent, glasswort biomass reached 10.0–11.3 kg FW m^{-2} in 74 days, clearly above the unfertilized control at 4.6 kg FW m^{-2} and above the seawater-irrigated *Salicornia* benchmark of >8 kg FW m^{-2} over 10–12 weeks [24,68]. By contrast, under imbalanced aquaponic water, harvested biomass fell to 0.58 kg m^{-2}, and in *S. europaea* even short-term biomass formation declined from about 0.47–0.48 to 0.25 g DW plant^{-1} when nitrate-containing nutrition was replaced by NH_4^+ alone [76,77]. Agronomically, aquaculture and IMTA-linked effluents should therefore be interpreted as the most productive saline wastewater option for *Salicornia* when nitrate is present, micronutrients are sufficient, and hydraulic exchange prevents progressive substrate salinization.

5.1.2. Greenhouse Drainage and Recirculating Hydroponic Waters

Greenhouse drainage and recirculating hydroponic waters can maintain *S. europaea* productivity when saline nutrient recycling keeps the crop within its functional growth range [21,25,71]. In a 63-day greenhouse pot trial, shoot fresh weight remained approximately 190 g plant^{-1} under the standard nutrient solution (SNS) and tomato hydroponic effluent (HE), declined slightly to about 170 g plant^{-1} under diluted aquaculture effluent (AE50), and reached about 150 g plant^{-1} under undiluted aquaculture effluent (AE100), but these differences were not significant [25]. Shoot dry weight likewise remained stable at roughly 17–19 g plant^{-1} across all four treatments, with no significant treatment effect, indicating that wastewater irrigation preserved biomass accumulation at the plant level rather than increasing or suppressing it relative to the control [25]. Dry matter content remained close to 9–10%, with approximate values of 10.0% in SNS, 9.4% in HE, 8.9% in AE50, and 10.2% in AE100, and the only significant effect detected was a modest shift in dry matter percentage [25].

Although biomass was maintained, shoot chemistry changed substantially under wastewater irrigation. Shoot nitrate concentration was about 3.9 g kg^{-1} FW in SNS and 3.1 g kg^{-1} FW in HE, but fell to about 0.9 g kg^{-1} FW in AE50 and 2.1 g kg^{-1} FW in AE100, while shoot sodium rose progressively from about 0.2 g kg^{-1} FW in SNS to 8.4 g kg^{-1} FW in HE, 12.4 g kg^{-1} FW in AE50, and 19.0 g kg^{-1} FW in AE100 [25]. The wastewater treatments therefore did not reduce biomass, but they did alter mineral composition in a direction consistent with increasing saline exposure [25]. Puccinelli et al. [25] also reported lower antioxidant compounds, pigments, and total antioxidant capacity in wastewater-grown

plants than in SNS plants, while catalase activity was higher under wastewater irrigation, indicating that the dominant response was biochemical adjustment rather than biomass loss.

Compared with the salinity optimum benchmark established by Hulkko et al. [15], in which *S. europaea* reached 4365 g total fresh biomass at 342 mM NaCl versus 1586 g at 0 mM NaCl, the greenhouse wastewater treatments maintained biomass but did not exceed the maximal saline-growth response [15]. Within the agronomic framework established for *Salicornia* cultivation, this pattern indicates biomass preservation under recycled saline water rather than biomass enhancement above the salinity optimum, and therefore should not be interpreted as evidence of optimal crop performance [15,21]. Thus, greenhouse drainage and recirculating hydroponic waters should be interpreted as systems capable of maintaining biomass production under saline wastewater irrigation, with shoot biomass remaining at approximately 150–190 g FW plant^{-1} and 17–19 g DW plant^{-1} across treatments [25]. However, this maintenance of biomass was accompanied by a reduction in shoot nitrate concentration from 3.9 to 0.9 g kg^{-1} FW, an increase in shoot sodium concentration from 0.2 to 19.0 g kg^{-1} FW, and changes in antioxidant metabolism, indicating physiological adjustment to saline stress despite the maintenance of biomass [25]. Consequently, biomass maintenance under these conditions should be interpreted as evidence of plant persistence and sustained short-term productivity, but not necessarily of optimal long-term productivity or biomass quality.

5.1.3. Municipal and Domestic Wastewaters

Municipal and domestic wastewaters supported measurable growth of *S. europaea*, but the response was more conditional and stage-dependent than in aquaculture- or greenhouse-based saline reuse systems. In the phytoremediation study of Khalilzadeh et al. [26], total plant biomass under wastewater irrigation increased from 367 ± 68.9 mg plant^{-1} at the short-term vegetative stage to 836 ± 29.72 mg plant^{-1} at the long-term reproductive stage, compared with 284 ± 60.7 mg plant^{-1} and 762 ± 123.46 mg plant^{-1}, respectively, in the corresponding control treatments [26]. Shoot biomass followed the same pattern, increasing from 350 ± 69 mg plant^{-1} at the vegetative stage to 780 ± 40 mg plant^{-1} at the reproductive stage under wastewater irrigation, while root biomass increased from 17 ± 0.81 to 56–57 mg plant^{-1} across the same interval [26]. These values show that municipal wastewater did not suppress biomass formation; instead, *S. europaea* remained productive throughout the cultivation cycle and reached its highest biomass at the reproductive stage [26].

The agronomic response was accompanied by wastewater-treatment functionality and clear physiological acclimation. In a companion study, *S. europaea* irrigated with wastewater achieved pollutant removal efficiencies of 61% for COD, 74% for BOD, 47.6% for TSS, and 64% for ammoniacal nitrogen at the reproductive stage, indicating that biomass accumulation and treatment performance occurred simultaneously [31]. Long-term wastewater exposure also increased stress-acclimation capacity, with catalase activity rising by 154%, peroxidase by 32%, and polyphenol oxidase by 57%, together with increases in chlorophyll, soluble proteins, proline, and soluble sugars [26,78]. Thus, the plant response was not a simple growth penalty; it was a combination of continued biomass accumulation and physiological adjustment under contaminant exposure.

The main agronomic constraint was the final quality of the biomass rather than its production. Wastewater-irrigated plants preferentially accumulated Zn and Pb in shoots, whereas Cu, Ni, and Cd were retained more strongly in roots, and transfer factors at flowering followed the order Zn > Pb > Ni > Cd > Cu [26]. Additional uptake studies also showed that *S. europaea* can accumulate pharmaceutical residues under irrigation exposure, although marked physiological effects were most evident only at the highest exposure level during a 21-day experiment [57]. Agronomically, municipal and domestic wastewaters

can therefore sustain useful *Salicornia* biomass production, but the harvested biomass is conditionally suitable and must be routed according to contaminant thresholds before it can be considered for food, feed, or other value-added uses.

5.1.4. Industrial and Agro-Industrial Brines

Industrial and agro-industrial brines generally constrained *Salicornia* productivity, with biomass response depending strongly on dilution, nutrient balance, and overall matrix quality. In *Salicornia bigelovii*, saline-water irrigation including aquaculture reject brine supported production, with fresh-tip yield reaching 649 g m^{-2} under managed leaching and dry forage yield of 2.0–2.6 kg m^{-2}, placing performance within the lower end of the saline cultivation range rather than above it [70]. In *Salicornia fruticosa*, agro-industrial compost leachate produced the highest yield among the tested nutrient solutions, reaching 5.41 kg m^{-2}, and foliar melatonin increased productivity to 6.08 kg m^{-2}, showing that biomass gains were possible when the leachate had a usable nutrient profile and crop management was optimized [53].

A similar pattern was observed in *Salicornia brachiata* under tannery soaking wastewater, where fresh and dry biomass increased up to 12,500 ppm NaCl after 90 days, reaching 6.86 g and 0.479 g, respectively, but declined at 15,000 ppm, indicating a narrow optimum and clear loss of productivity at higher stress [79]. Additional hydroponic evidence from the Kansas State University thesis also indicates that industrial water composition influences *Salicornia* performance under controlled culture, reinforcing that productivity under these waters is matrix-dependent rather than salinity-dependent alone [65].

Overall, industrial and agro-industrial brines supported *Salicornia* growth only when the saline input remained within a manageable range; otherwise, co-toxicity, nutrient imbalance, and excessive osmotic load reduced biomass formation. Compared with optimized saline cultivation benchmarks, these systems should therefore be interpreted as conditional production environments, where acceptable yields are achievable but rarely robust without dilution, leaching control, or other management inputs [53,65,70,79].

5.1.5. Desalination Brines

Desalination concentrates are typically high in total dissolved solids but poor in plant-available nutrients, so biomass outcomes for *Salicornia* are driven more by resource limitation and system design than by salt tolerance per se [8,54,80]. Integrated FO–RO–FO designs that adjust RO reject concentration and couple brine reuse with halophyte cultivation can produce agronomically meaningful yields: modelling and pilot analyses show up to 4.9 kg edible halophyte m^{-2} of groundwater withdrawn under an FO–RO–FO groundwater-treatment configuration, demonstrating that desalination-linked reuse can generate usable biomass when brine concentration and water balance are engineered for crop demand [61]. Experimental hydroponic tests with RO brines (6–9 g L^{-1}) confirm that halophytes remain viable across realistic brine salinities and that growth traits, notably root development and tissue Na/K accumulation, respond to increasing brine concentration, indicating active brine uptake and physiological acclimation within the tested range [81]. However, in most practical applications untreated desalination concentrate is growth-limiting because of low nitrogen and micronutrient supply; therefore, acceptable areal productivity is generally achieved only after blending with nutrient-bearing streams, fertilization, or use within a managed reuse system that provides co-nutrients and leaching control [6,8,54,61,80]. Agronomically, desalination brine systems are thus best characterised as conditional-production environments: survival and some growth are common, but robust biomass yields comparable to optimized saline cultivation require explicit nutrient correction and hydraulic design [61,81].

Table 1. Agronomic performance patterns of *Salicornia* under different saline wastewater classes.

Wastewater Class	Taxon	Experimental Conditions	Growth Response	Agronomic Limitation	References
Seawater cultivation benchmark	*Salicornia* spp.	Field cultivation under seawater irrigation over approximately 10–12 weeks, with harvest interval management	Cumulative fresh biomass exceeded 8 kg FW m^{-2}; 3-week harvest interval gave the highest productivity	Productivity depended on harvest interval, regrowth capacity, and saline management	[68]
Hydroponic salinity benchmark	*Salicornia europaea*	Hydroponic salinity gradient from 0 to 342 mM NaCl	Total fresh biomass increased from 1586 g at 0 mM NaCl to 4365 g at 342 mM NaCl	Non-saline conditions suppressed biomass; optimum growth occurred at 342 mM NaCl	[15]
Diluted seawater benchmark	*Salicornia bigelovii*	Field irrigation with seawater dilution and fertilization	Best treatment produced 2781 g m^{-2} FW, 1328 g m^{-2} DW, and 286 g m^{-2} seed yield; best combined irrigation + fertilization treatment reached 3218 g m^{-2} FW, 1576 g m^{-2} DW, and 413 g m^{-2} seed yield	Biomass and seed production increased with nutrient supplementation and optimized irrigation	[69]
Aquaculture/IMTA effluent	*Sarcocornia neei*	74 days in drainage lysimeters under $NH_4^+ + NO_3^-$, NO_3^-, and unfertilized seawater treatments	11.3 ± 2.0 kg FW m^{-2}, 10.0 ± 0.8 kg FW m^{-2}, and 4.6 ± 0.6 kg FW m^{-2}, respectively	Yield depended on nutrient supply and drainage; insufficient leaching increased root-zone salt accumulation	[24]
Aquaculture wastewater/RAS nutrients	*Salicornia europaea*	Aquaculture-like nutrient conditions with NH_4^+, NO_3^-, and NH_4NO_3 treatments	Final biomass was ~0.25 g DW $plant^{-1}$, 0.35 g DW $plant^{-1}$, and 0.47–0.48 g DW $plant^{-1}$, respectively	Nitrogen speciation constrained growth; ammonium alone was least productive	[76]
Greenhouse drainage/hydroponic recirculates	*Salicornia europaea*	63-day pot trial with standard nutrient solution, tomato hydroponic effluent, diluted aquaculture effluent, and undiluted aquaculture effluent	Shoot biomass remained stable at ~150–190 g FW $plant^{-1}$ and ~17–19 g DW $plant^{-1}$ across treatments	Biomass was maintained despite physiological adjustments associated with saline stress	[25]
Municipal wastewater irrigation	*Salicornia europaea*	Field irrigation under wastewater exposure overgrowth stages	Biomass increased from 367 ± 68.9 to 836 ± 29.72 mg $plant^{-1}$ from vegetative to reproductive stage; shoot biomass increased from 350 ± 69 to 780 ± 40 mg $plant^{-1}$	Growth was maintained, but heavy-metal accumulation limited edible use	[26]
Industrial wastewater exposure	*Salicornia brachiata*	90-day tannery soaking wastewater exposure under increasing NaCl	Fresh biomass peaked at 6.86 g and dry biomass at 0.479 g at 12,500 ppm NaCl, then declined at 15,000 ppm	High salinity and co-toxic industrial compounds limited growth	[79]
Agro-industrial compost leachate	*Salicornia fruticosa*	Cascade cropping with compost leachate, peat leachate, nutrient solutions, and melatonin supplementation	Highest yield reached 5.41 kg m^{-2} under compost leachate and 6.08 kg m^{-2} with melatonin	Nutrient composition and cultivation management controlled productivity	[53]
Desalination brines	*Salicornia* spp.	FO-RO-FO reuse and hydroponic brine cultivation at 6–9 g L^{-1}	Up to 4.9 kg edible halophyte m^{-3} groundwater withdrawn; strongest root development at 9 g L^{-1}	Nutrient scarcity and brine concentration limited biomass unless supplemented; yields remained below saline benchmark levels	[61,81]
Synthetic NaCl baselines	*Salicornia* spp.	Controlled salinity-gradient experiments	Biomass was lower at 0 mM NaCl; optimum growth generally occurred at ~200–400 mM NaCl	Productivity declined outside the physiological salinity optimum	[15,17,21]

5.1.6. Synthetic NaCl Baselines

Synthetic NaCl gradients establish the physiological production window that must be used as the agronomic benchmark for interpreting real-effluent outcomes, because they isolate salinity from co-stressors and operational drift [17,21]. Controlled studies consistently show that *Salicornia* taxa produce less biomass at 0 mM NaCl than at moderate salinity and that biomass commonly peaks within a moderate salinity band, approximately 200–400 mM NaCl for many ecotypes, with the exact optimum varying by species and provenance [15,17]. For example, hydroponic experiments reported markedly higher total fresh biomass at optimum salinity than under non-saline control, demonstrating that moderate saline stress promotes succulence and vegetative growth rather than suppressing it. Mechanistic and molecular analyses confirm that this optimum reflects adaptive osmotic and ionic partitioning that maximizes tissue expansion and water content within a defined ionic window, after which biomass declines as osmotic and ionic load or nutrient limitation intensify [15,17]. Therefore, comparisons of desalination- or wastewater-irrigated *Salicornia* should be made against the synthetic-NaCl production benchmark, the moderate-salinity optimum, rather than against freshwater controls: brines that fall outside this window, either too dilute in halophilic stimulus, too nutrient-poor, or too concentrated or contaminated, will predictably deliver lower biomass despite plant survival [15,17,21].

Across wastewater classes, several consistent patterns emerge. When interpreted against synthetic NaCl benchmarks, biomass performance was influenced less by salinity itself than by nutrient availability, wastewater composition, and cultivation management, provided that *Salicornia* was grown within its physiological tolerance range. Aquaculture and IMTA-linked effluents generally supported the highest productivity because they combined saline conditions with a relatively balanced nutrient supply, whereas greenhouse drainage and recirculating hydroponic waters primarily maintained biomass rather than enhancing it. Municipal wastewaters were capable of sustaining biomass production and simultaneous pollutant removal but introduced greater uncertainty regarding biomass quality and end-use safety due to contaminant accumulation. Industrial and agro-industrial brines showed the greatest variability in productivity, reflecting stronger influences of co-toxicity, nutrient imbalance, and wastewater-specific matrix effects. Desalination brines were distinguished by nutrient scarcity rather than excessive salinity, making biomass production highly dependent on nutrient supplementation and system design. Taken together, these studies indicate that the agronomic feasibility of saline wastewater reuse for *Salicornia* depends primarily on nutrient sufficiency, wastewater quality, and management practices, while salinity becomes a secondary constraint once cultivation occurs within the crop's adaptive range.

5.2. Biomass Composition, Functional Quality, and Safety Signals

Performance studies frequently report biomass-composition endpoints that determine whether harvested *Salicornia* can be routed to food, feed, or non-food applications. Under saline irrigation, shoots accumulate Na^+ and Cl^- and often exhibit reduced K:Na ratios, increasing ash content and influencing taste, texture, processing requirements, and dietary positioning for edible markets [21,67,75]. Nutrient-rich saline effluents can also increase tissue nitrogen and protein, supporting vegetable or forage potential, but this value remains conditional on contaminant profiles and final biomass composition [21,25].

In edible-shoot systems, agronomic performance must therefore be interpreted not only as total biomass, but also as marketable biomass. Wastewater irrigation can modify shoot succulence, branching, mineral load, and the timing of lignification, all of which affect sensory quality and commercial value. Harvest regime is a key management factor within this context. In saline aquaponics with *Sarcocornia neei*, cutting management altered

branching architecture and marketable branch proportion: treatments with no cutting or a single 28-day cutting interval produced approximately 26–40% of branches reaching commercial size (≥10 cm), whereas frequent 14-day cutting generated many short branches with lower marketable value [74]. Thus, realised yield in wastewater-linked systems depends on the interaction between water quality, plant architecture, and harvest timing, rather than on biomass quantity alone [21,74,75]. These composition, quality, and safety signals are summarised in Table 2.

Table 2. Quality and safety signals reported in *Salicornia* agronomic performance studies under saline wastewater irrigation.

Signal	What Is Reported	Agronomic or Safety Implication	References
Mineral load (Na^+, Cl^-; ash content)	High shoot Na^+ and Cl^- accumulation and reduced K:Na ratios under saline irrigation	Elevated ash and mineral content can constrain edible biomass routing and require mineral profiling alongside yield reporting	[21,67]
Protein/nitrogen enrichment	Increased tissue N and protein concentrations under nutrient-rich saline effluents	Supports food or forage potential when contaminant loads remain controlled	[21,25]
Harvest-managed marketable fraction	Cutting regime altered marketable branch proportion (~26–40% under 28-day or no-cut regimes vs. lower proportions under frequent cutting)	Realised edible yield depends partly on harvest management rather than wastewater chemistry alone	[74]
Metal partitioning under municipal irrigation	Shoots accumulated Zn and Pb while Cd, Cu, and Ni showed stronger root retention patterns	Biomass productivity may coexist with food-safety constraints, requiring monitoring of metal accumulation	[26]
Pharmaceutical uptake potential	Carbamazepine uptake and translocation detected in *S. europaea* under controlled exposure	Indicates potential transfer of pharmaceutical residues to plant biomass when municipal wastewater is used	[57]

Safety-relevant signals are particularly important when municipal or mixed-origin wastewaters are used. Under heavy-metal-polluted municipal wastewater irrigation, *S. europaea* accumulated Zn and Pb in shoots, while Cd, Cu, and Ni showed stronger root-biased retention, indicating that biomass production can coexist with food/feed safety constraints [26]. Controlled uptake studies further show that pharmaceuticals can be transferred into plant tissues; for example, carbamazepine uptake and translocation into *S. europaea* have been reported under experimental exposure [57]. Therefore, high biomass production under wastewater irrigation should not be interpreted as automatic biomass valorisation. End-use decisions require mineral, metal, and emerging-contaminant screening, especially when biomass is intended for food, feed, or high-value bioproducts.

5.3. Management and Regime Effects

Only a subset of the literature treats management as an experimental driver, but the available evidence indicates that irrigation regime, nutrient supply, harvest strategy, and system operation all influence *Salicornia* performance beyond the effect of salinity alone [68,74,82]. In *Sarcocornia neei* progenies, saline irrigation scheduling affected vegetative growth, reproductive allocation, and mineral composition, indicating that irrigation regime influences biomass partitioning and harvest timing rather than merely determining final biomass totals [82]. Comparable evidence in *S. europaea* further shows that irrigation salinity and ecotype jointly alter shoot growth, seed yield, and tissue ion accumulation, confirming that agronomic performance depends on how salinity is managed, not simply on whether the crop survives under saline conditions [15,83].

Once salinity is within the crop's tolerance range, nutrient management becomes a major determinant of biomass production. Under aquaculture-linked nutrient conditions, *S.*

europaea produced substantially more biomass under nitrate-containing or mixed nitrogen supply than under ammonium alone, demonstrating that nitrogen speciation directly affects growth and biomass allocation [76]. This is consistent with field evidence showing that diluted seawater combined with fertilization can markedly improve growth, seed yield, and nutrient status in *Salicornia* cultivation, particularly when salinity remains within the productive range of the crop [69]. In practical terms, saline cultivation performance should therefore be interpreted primarily through nutrient sufficiency and nitrogen form once osmotic stress is not the main limitation [69,76]. This interpretation is reinforced by saline aquaponic nutrient synthesis showing that nitrogen and phosphorus requirements can become limiting under prolonged recirculation and that nutrient form and concentration must be actively managed to sustain halophyte productivity [84].

Harvest and canopy management also determine the proportion of biomass that is commercially usable. In saline aquaponics with *Sarcocornia neei*, cutting regime altered branching architecture and biomass quality: plants subjected to no cutting or to a 28-day cutting interval produced a higher proportion of commercial-size shoots, whereas frequent 14-day cutting generated many short branches with lower marketable value [74]. Thus, realised productivity in *Salicornia* systems is partly a harvest-design outcome, because agronomic yield depends on the interaction between biomass accumulation, canopy structure, and marketable fraction rather than on total biomass alone [74,75].

Operational management is particularly important in aquaponic and recirculating systems, where crop performance depends on more than bulk water chemistry. Solids handling, water clarification, and recirculation conditions act as agronomic controls because they influence nutrient availability, water quality, and the stability of the root environment over time [84,85]. As a result, similar nominal effluent chemistry does not necessarily produce similar crop performance when the operational context differs. Taken together, the evidence indicates that successful *Salicornia* cultivation under saline or wastewater-based systems depends on integrated agronomic management of irrigation regime, nutrient supply, harvest strategy, and system operation, rather than on salt tolerance alone [82,85,86]. Across cultivation systems, management-related variables consistently explained a substantial proportion of the observed variation in biomass performance, often exceeding the influence of salinity alone once the crop remained within its physiological tolerance range.

5.4. Substrate and Cultivation Mode as Performance Drivers

Cultivation mode controls how quickly the root zone drifts in salinity and co-contaminants, and therefore how stable the yield remains over time. Hydroponics and aquaponics enable control of EC and N form but require active management of solids and nutrient balance to prevent inhibition from ammonium or micronutrient imbalance [76,86]. Constructed wetlands prioritize treatment reliability and often report biomass as a co-product, with performance sensitive to hydraulic regime and media effects [24,46]. In soil-based seawater irrigation, yield components and nutritional status can respond to fertility amendments, while long-term stability depends on salt balance at the system level [64,68].

Long-duration aquaculture effluent evidence shows that salt mass balance can dominate performance. In RAS effluent lysimeters, leachate fraction is explicitly framed as necessary to flush salts and optimize halophyte growth, and biomass differences align with leaching treatments, supporting a substrate-driven constraint that is only visible in longer trials [66]. This is consistent with broader halophyte agronomy, where evapotranspiration concentrates salts, and management must maintain a leaching or exchange pathway to avoid progressive yield decline [21,66].

5.5. Species and Ecotype Differences Under Saline Waters

Genotype effects remain under-tested relative to their likely importance for scale-up, but available studies indicate meaningful variation in quality traits under salinity [75]. Forage-quality assessment across *Salicornia persica* ecotypes under salinity reports ecotype-dependent differences in protein and fibre metrics, implying that cultivar selection can shift usable biomass quality even within comparable stress envelopes [87]. In saline aquaponics, progeny-dependent responses of *S. neei* to irrigation schedules further indicate within-species variability in performance within a shared operational chemistry space [82].

Overall, agronomic performance under saline wastewater irrigation reflects the interaction of wastewater chemistry, nitrogen availability, hydraulic salt balance, and management regime rather than salinity tolerance alone. These constraints define the productivity envelope within which Salicornia operates and provide context for examining contaminant-removal pathways for each wastewater class.

6. Phytoremediation Functions and Mechanisms of *Salicornia* in Saline Wastewater Systems

Within the biomass and operational envelope defined in Section 5, the central question becomes which contaminant classes are removed, at what reliability, and through which dominant sinks. Across saline constructed wetlands (CWs), aquaculture-linked polishing modules (RAS and IMTA), hydroponic systems, and field irrigation settings, most studies report changes in influent-effluent concentrations, soil–plant gradients, or tissue concentrations. However, relatively few close full mass balances that partition removal among plant assimilation and harvest, microbial transformations such as nitrification-denitrification, and substrate or sediment storage. As a result, reported removal efficiencies must be interpreted as system- and design-conditional rather than intrinsic plant properties, particularly for salts and micropollutants where fate tracking is limited [30,46,49,50,88,89].

Where salinity is experimentally manipulated, it can alter pathway dominance even when overall removal appears stable. In saline wetland systems, increasing salinity has been shown to reduce COD removal while maintaining, or in some cases promoting, nitrogen removal, consistent with shifts in microbial community structure and functional gene abundance under salt stress [90]. These observations reinforce a key interpretation throughout this section: removal performance arises from the interaction among plant physiology, microbiome dynamics, hydraulics, and substrate properties rather than from plant uptake alone. The main pathways for contaminant removal in *Salicornia*-based saline wastewater systems are shown in Figure 2.

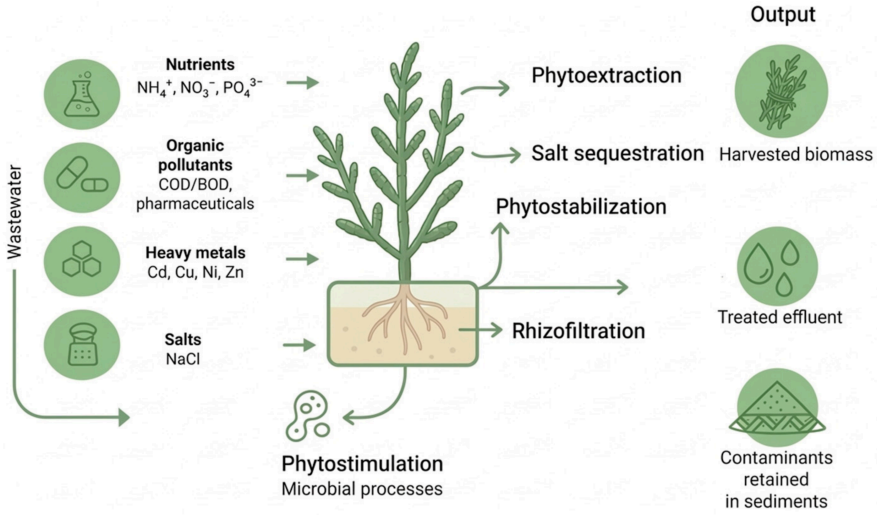


Figure 2. Phytoremediation pathways in *Salicornia*-based saline wastewater systems.

6.1. Nutrients and Organic Load: Pathway Dominance Under Saline Conditions

In saline constructed wetlands treating aquaculture and mariculture effluents, total nitrogen and dissolved inorganic nitrogen (DIN) removal is frequently reported at high levels. However, attribution varies depending on wetland configuration, redox zonation, hydraulic retention time, and loading rate [30,46,49,50,52,88]. Across systems where mechanisms are resolved, microbial transformations, particularly coupled nitrification and denitrification, represent dominant nitrogen sinks at higher loadings, whereas plant assimilation becomes proportionally more relevant when biomass production is strong and specific loading per unit area is lower.

Nutrient recovery pilots using *S. neei* under marine salinity conditions further support the treatment's feasibility. Nitrogen removal efficiencies in aquaculture effluent systems have been reported in the upper range (approximately 80% to 90%) while simultaneously producing harvestable biomass, demonstrating the compatibility of treatment and production objectives [24,46].

Nitrogen speciation plays a critical operational role. Under aquaculture-relevant nutrient conditions, *Salicornia* growth and nitrogen uptake are reduced when ammonium is supplied as the sole nitrogen source compared to nitrate or mixed nitrogen forms, indicating that DIN removal depends not only on concentration but also on nitrogen form and associated pH–redox dynamics [76]. Nutrient-requirement studies in saline aquaponics systems similarly identify nitrogen form and phosphorus availability as binding constraints that shape both biomass accumulation and nutrient capture efficiency [23,86].

In saline wetlands and aquaculture polishing systems, phosphorus removal is predominantly driven by substrate- and sediment-bound processes, including sorption, precipitation, and sedimentation. Plant phosphorus storage typically represents a smaller fraction of cumulative phosphorus retention, particularly during longer-term operation [46,49,50,89]. Consequently, apparent total phosphorus removal may be high during early system operation but becomes saturation-limited over time, making long-term performance dependent on media selection, hydraulic design, and maintenance rather than on halophyte identity alone.

Reductions in chemical oxygen demand (COD) and biochemical oxygen demand (BOD) in saline systems are primarily mediated by microbial degradation and physical retention mechanisms, including biofilm activity and sedimentation. *Salicornia* primarily functions as a rhizosphere engineer, structuring oxygen gradients, supplying root exudates, and stabilising microbial communities rather than directly degrading complex organic compounds [30,46,88]. Experimental evidence indicates that increasing salinity can depress COD removal in some constructed wetland configurations, highlighting the need to adapt freshwater wetland design principles when operating under saline conditions [89,90].

6.2. Salts and Ions: Realistic Phytodesalination and Salt-Balance Limits

Ion sequestration enables *Salicornia* to survive and remain productive under high salinity, yet net salt removal from treated matrices is generally constrained by harvest-mediated export and by evapotranspiration-driven concentration of residual salts. Sodium and chloride concentrations in shoot tissues can reach approximately 10–20% of dry weight, depending on species, growth stage, and salinity level [17,21]. When combined with realistic biomass yields, harvest-mediated salt export can be quantified; however, the exported salt mass is typically small relative to the salt loads present in many saline wastewaters and soils [71,72].

Hydroponic experiments provide proof-of-principle evidence for salinity reduction under controlled conditions. In *Sarcocornia/S. neei* systems, measurable reductions in electrical conductivity and NaCl concentration have been observed over multi-week periods, including reductions of approximately one-third at specific salinity setpoints [91]. However,

interpretation requires careful accounting for evaporation, dilution, and complete salt mass balances across biomass, water, and substrate compartments. Accordingly, the most defensible general conclusion is that *Salicornia* contributes to limited phytodesalination through incremental salt export and salt stabilization, rather than serving as a replacement for engineered desalination technologies [46,89].

A major research gap is the limited availability of long-duration, multi-cycle salt balance studies that track ion distribution across repeated harvests and incorporate leaching, drainage, and substrate accumulation dynamics. Such studies are required to quantify the long-term contribution of harvest-mediated salt export relative to the total salt loads entering saline wastewater treatment systems.

6.3. Heavy Metals and Metalloids: Partitioning and Routing Implications

In municipal wastewater irrigation with elevated heavy metal concentrations, *Salicornia* exhibits element-specific partitioning patterns consistent with a mixed phytoremediation mode. For *S. europaea*, higher shoot concentrations have been reported for some elements such as lead and zinc, while cadmium, copper, and nickel tend to accumulate preferentially in roots and rhizosphere sediments [26]. These patterns indicate the coexistence of phytoextraction (harvest-exportable fraction) and phytostabilisation (root-zone immobilisation).

Because root-zone immobilisation can dominate for several metals, reductions in bioavailable pools may reflect sorption, precipitation, and rhizosediment binding as much as tissue export, particularly in saturated soils or constructed wetlands [46,89]. This partitioning has direct implications for biomass routing. Where shoot accumulation is substantial, harvesting can remove contaminants but may restrict food or feed applications. Where stabilisation dominates, system performance relies more on sediment management and controlled disposal pathways than on biomass export.

6.4. Pharmaceuticals and Emerging Contaminants

Evidence for pharmaceutical removal remains proof of concept relative to nutrients and metals. Controlled exposure studies demonstrate compound-dependent uptake and translocation in *Salicornia*, including detection of carbamazepine in plant tissues and partial removal from solution [57]. However, field-scale removal efficiencies, identification of transformation products, and multi-cycle accumulation data remain scarce. Moreover, the relative contributions of plant uptake, microbial degradation, and substrate sorption are rarely resolved under saline conditions [46,92]. For regulatory and risk assessment contexts, percent removal alone is insufficient if metabolites persist or if repeated harvest cycles concentrate residues in biomass destined for valorisation. Accordingly, pharmaceutical monitoring should be integrated with contaminant-aware biomass routing, ensuring that end-use decisions are guided by contaminant thresholds, processing requirements, and the intended valorisation pathway.

6.5. Mechanistic Integration Under Saline Operation

Across contaminant classes, *Salicornia*-based systems express a mechanism portfolio whose dominance is determined by wastewater chemistry and system configuration [49,50]. Phytoextraction is most defensible for nutrients and selected metals where shoot accumulation and harvest occur [26,50]. Rhizofiltration is relevant in flow-through hydroponic and inlet wetland zones where dissolved constituents interact with dense root systems and biofilms [30,46]. Phytostabilisation dominates for many metals and a substantial fraction of phosphorus retention, with substrates and sediments functioning as primary sinks [26,89]. Phytostimulation underpins COD removal and nitrogen transformations by structuring the rhizosphere and enhancing microbial activity [30,90]. Salt sequestration and harvest-

mediated export occur through ion storage in succulent tissues, but net salinity reduction remains system-conditional and scale-limited [46,49,91].

6.6. Integrated Design Rule and Cross-Cutting Gaps

Synthesis across contaminant classes supports a practical design rule: wastewater chemistry determines the potentially removable fraction, whereas system configuration and hydraulics determine the dominant removal sink [49,50,89,90]. Microbial processes dominate nitrogen and much COD removal [30,90]; substrate and sediment processes dominate phosphorus and many metals [46,89]; harvest export contributes meaningfully for a portion of nutrients and selected metals [26,50] but only incrementally for salts [71,91].

Key scaling gaps remain: limited full mass balances for nitrogen and phosphorus [50,71], insufficient long-term salt balance studies across repeated harvest cycles [89,91], sparse field-scale micropollutant fate datasets including metabolites [46,57], and weak integration between treatment outcomes and enforceable biomass routing constraints when wastewater complexity increases [46,92].

Because removal is frequently system-dominated for nutrients and organic load, harvest-limited for salts, and partitioning-sensitive for metals and micropollutants, *Salicornia* should be regarded primarily as an ecosystem engineer that facilitates phytoremediation by supporting rhizosphere microbial activity, oxygen transfer, and favourable physicochemical conditions, rather than as the principal direct scavenger for all contaminants. Taken together, the available evidence indicates that contaminant removal in *Salicornia*-based systems is governed more by the interaction between plant traits, microbial processes, and system design than by plant uptake alone, explaining much of the variability reported across wastewater types and treatment configurations. The next section evaluates how these pathway partitions constrain and enable safe and economically realistic biomass routing under each wastewater class.

7. Cultivation Systems and Engineering Design Levers

Cultivation system is a primary determinant of *Salicornia* performance because it shapes not only treatment function but also plant health, biomass accumulation, and final biomass quality. Across saline wastewater applications, the relevant question is therefore not the engineering configuration in isolation, but how that configuration influences crop productivity, physiological stability, and the suitability of the harvested biomass for food, fodder, remediation, or bioenergy uses [46,49,51]. In this sense, cultivation form acts as a practical filter on performance: systems that stabilise salinity and nutrient supply support stronger and more uniform plant development, whereas less controlled systems may preserve treatment function but reduce agronomic consistency [21,30,49].

Constructed wetlands and soil-based systems are most appropriate when *Salicornia* is used primarily as part of a treatment–production interface. In these systems, biomass is generally a co-product rather than the principal output, and the main advantage lies in treatment stability and phytoremediation capacity rather than in maximizing edible yield [46,49,50,52]. Wetland-based *Salicornia* systems have been shown to remove nitrogen, phosphorus, and suspended solids from saline mariculture effluents, while wastewater-irrigated *S. europaea* maintained biomass accumulation despite uptake of potentially toxic elements, with metal partitioning consistent with phytoextraction for Zn and Pb and phytostabilisation for Cu, Ni, and Cd [26,50,51]. These systems therefore offer the strongest phytoremediation value, but they are less suitable for uniform edible biomass because contaminant exposure and hydraulic variability reduce predictability in biomass quality [26,46].

By contrast, hydroponic, floating, and recirculating systems provide stronger control over the factors that drive *Salicornia* productivity. In hydroponic culture, *Salicornia europaea*

produced more harvestable biomass than in sand culture, confirming that controlled soilless systems can improve agronomic output when saline conditions are optimized [71]. In greenhouse recirculating systems irrigated with saline effluents, shoot biomass remained around 150–190 g fresh weight plant^{-1} and 17–19 g dry weight plant^{-1} showing that productive growth can be maintained when salinity and nutrient supply remain balanced [25]. Likewise, in a floating cascade system supplied with agroindustrial leachates, *S. fruticosa* reached 5.41 kg m^{-2}, and productivity increased to 6.08 kg m^{-2} with melatonin treatment, although the best nitrogen-use efficiency and phytochemical profile occurred under peat leachate rather than the highest-yielding compost leachate [53]. These findings indicate that the most productive cultivation system is not always the one that gives the highest product quality, and that biomass quantity and biomass suitability must be evaluated together [25,53].

IMTA-linked systems occupy an intermediate position between production and phytoremediation. In these systems, *Salicornia* can combine dissolved nutrient capture with biomass production, which makes them especially relevant when the objective is simultaneous nutrient recovery and crop valorisation rather than phytoremediation alone [23,50]. Their agronomic value depends on recirculation management, nitrogen form, and electrical conductivity control, because these factors determine whether biomass remains marketable or shifts toward lower-quality material [25,93]. Overall, hydroponic and floating systems are the strongest options for controlled biomass production, IMTA systems provide a compromise between production and nutrient recovery, and constructed wetlands are the most robust systems when phytoremediation and treatment stability are the primary objectives. Based on these agronomic and phytoremediation criteria, Table 3 summarises the suitability of the main cultivation systems for saline wastewater reuse in *Salicornia*, highlighting their effects on crop performance, remediation role, and feasible biomass route.

Table 3. System selection matrix for *Salicornia*-based saline wastewater treatment systems.

Wastewater Class	Preferred Cultivation System	Agronomic Performance	Main Phytoremediation Role	Key Management Control	Feasible Biomass Route
Aquaculture/IMTA effluent	Hydroponic systems or IMTA modules coupled to recirculating aquaculture systems	Strong biomass production under balanced saline nutrient supply; productive growth is maintained when recirculation and nitrogen delivery are controlled	Nutrient capture coupled to biomass production	Recirculation management, nitrogen speciation control, EC regulation	Food or fodder biomass where contaminant levels are controlled
Greenhouse drainage and recirculating hydroponic waters	Hydroponic recirculating systems	Stable shoot growth and biomass retention; approximately 150–190 g FW plant^{-1} and 17–19 g DW plant^{-1} have been reported under saline reuse	Mainly nutrient reuse and recycling rather than intensive phytoremediation.	EC monitoring, nutrient balancing, recirculation management	Edible biomass or high-value vegetable production
Municipal and domestic wastewater	Constructed wetlands or soil-based irrigation systems	Productive but more variable; biomass can be maintained under contaminant exposure, although quality is less predictable	Strong nutrient removal and metal uptake/partitioning	Hydraulic retention time, redox control, sediment and substrate management	Bioenergy biomass or phytoremediation applications
Industrial and agro-industrial wastewaters	Constructed wetlands with dilution or pretreatment	Conditional productivity; in floating cascade culture, yields reached 5.41 kg m^{-2} and 6.08 kg m^{-2} with melatonin, but biomass quality depended on the feed stream	Sorption, microbial degradation, and partial phytostabilisation.	Pretreatment, staged hydraulic treatment, and loading rate control	Remediation biomass or bioenergy feedstock

Table 3. *Cont.*

Wastewater Class	Preferred Cultivation System	Agronomic Performance	Main Phytoremediation Role	Key Management Control	Feasible Biomass Route
Desalination brines	Blended hydroponic or engineered wetland systems with nutrient supplementation	Growth is feasible only when nutrient limitation is corrected; otherwise biomass production is constrained	Salt sequestration and partial nutrient uptake.	Nutrient supplementation, EC regulation, controlled blending with nutrient-rich streams	Conditional biomass production or salt-tolerant forage

8. Biomass Valorisation and Safety

The potential use of *Salicornia* biomass produced under saline wastewater irrigation depends primarily on wastewater chemistry and resulting tissue composition rather than on biomass productivity alone. Under aquaculture-derived effluents and controlled hydroponic systems, studies generally report stable biomass production under defined influent conditions, supporting the feasibility of edible biomass production where water quality is controlled and contaminant burdens are limited [23,25,50]. In these systems, nutrient recovery is directly coupled to shoot production, while saline cultivation also promotes the accumulation of minerals, dietary fibre, and antioxidant compounds characteristic of halophytic vegetables [21].

By contrast, biomass routing becomes substantially more restrictive under municipal or industrial wastewater regimes. Under heavy-metal-polluted municipal wastewater irrigation, *S. europaea* accumulated Zn and Pb in shoots, while Cd, Cu, and Ni showed stronger retention in belowground tissues, indicating contaminant-specific partitioning rather than complete exclusion [26]. Controlled exposure studies further show that pharmaceuticals such as carbamazepine can be absorbed and translocated into aerial tissues [57]. These findings indicate that high biomass productivity does not necessarily imply suitability for food or feed applications without contaminant verification.

Animal-feeding studies demonstrate that *Salicornia* biomass produced under controlled saline irrigation (e.g., seawater) can replace part of conventional forage without adverse effects on animal performance and may improve antioxidant status while reducing in vitro methane production [94,95]. However, these findings should not be extrapolated to biomass produced using contaminated wastewaters. Where *Salicornia* biomass is produced under wastewater conditions that result in elevated heavy-metal accumulation [26], feed applications should only be considered following batch-specific contaminant verification and compliance with regulatory limits. Otherwise, routing biomass toward non-food applications remains the most appropriate strategy to minimise the transfer of heavy metals, pharmaceuticals, and other trace contaminants into the food chain.

Consequently, the feasibility of biomass valorisation depends on the origin and chemical complexity of the wastewater source. Aquaculture and greenhouse recirculating effluents may support edible or forage applications under controlled monitoring, whereas municipal and industrial wastewaters generally require contaminant screening before biomass utilisation [46,55]. Under systems characterised by metals, pharmaceuticals, or high organic loads, routing biomass toward non-food applications may represent the safest strategy to minimise food-chain transfer risks. Overall, current evidence indicates that biomass valorisation under saline wastewater irrigation should be interpreted as a contaminant-aware routing problem, in which the suitability of *Salicornia* biomass for food, feed, or industrial applications depends on wastewater chemistry, contaminant fate, and resulting tissue composition under each cultivation regime.

9. Future Perspectives

Current evidence indicates that *Salicornia*-based saline wastewater systems have progressed beyond proof-of-concept studies and are now entering a phase where large-scale operational validation becomes the primary research priority. Future development should therefore focus on multi-year, field-scale trials operating under realistic hydraulic and chemical variability while incorporating complete nutrient and contaminant mass balances. Although nitrogen and organic-load attenuation have been consistently demonstrated in aquaculture-linked systems and saline constructed wetlands, the relative contributions of plant uptake, microbial transformation, and substrate retention remain insufficiently resolved under prolonged saline loading [30,49]. Long-term studies are particularly needed to quantify salt accumulation, phosphorus saturation, contaminant partitioning, and hydraulic stability across repeated harvest cycles. In this context, removal percentages alone are insufficient descriptors of performance; scalable implementation requires harmonised reporting of areal removal rates, hydraulic loading, biomass-normalised nutrient export, and contaminant fate under operational conditions [46].

A second major frontier lies in the transition from passive phytoremediation systems to deliberately engineered plant–microbe reactors. Across wastewater classes, treatment performance is repeatedly governed by hydraulic configuration, oxygen distribution, microbial niche stability, and solids management rather than by plant uptake alone [46,49]. Future saline treatment systems should therefore integrate staged oxic–anoxic compartments, controlled hydraulic exchange, media optimisation, and microbiome-informed engineering to stabilise coupled nitrification–denitrification processes under saline conditions. In parallel, omics-guided genotype selection and targeted inoculation with plant growth-promoting rhizobacteria may provide new opportunities to align *Salicornia* ecotypes and rhizosphere function with specific wastewater chemistries, thereby improving resilience, nutrient recovery, and contaminant attenuation under fluctuating salinity regimes.

Future progress will also depend on embedding *Salicornia* cultivation within circular bioeconomy and brine-management frameworks. Productive deployment requires integrating wastewater treatment reliability with contaminant-aware biomass routing, processing validation, and techno-economic feasibility. Consequently, future pilot systems should define contaminant thresholds for edible and non-food biomass pathways, evaluate processing and fractionation strategies where necessary, and incorporate life-cycle assessment, cost analysis, land-use considerations, and long-term operational performance alongside agronomic and remediation performance. Particular attention is required for metals, pharmaceuticals, and other trace contaminants whose long-term accumulation and transfer into biomass, sediments, or downstream processing streams remain poorly resolved [26,57]. Ultimately, multi-site demonstration systems combining hydraulic optimisation, agronomic productivity, contaminant mass-balance closure, and validated valorisation pathways represent the most direct route for transforming *Salicornia*-based saline wastewater treatment from conditional feasibility into operational infrastructure suitable for safe, economically viable, and regulatorily defensible deployment.

10. Conclusions

This review positions *Salicornia* spp. as keystone halophytes capable of coupling biomass production with phytoremediation across a range of saline wastewater conditions. Their physiological capacity for ion compartmentalisation, nutrient uptake, osmotic regulation, and oxidative stress buffering enables integration into constructed wetlands, hydroponic systems, and irrigated saline soils under conditions that exclude conventional crops.

The strongest evidence is for nutrient-rich saline effluents derived from aquaculture and controlled hydroponic systems, where consistent nitrogen attenuation and harvestable

biomass production have been achieved under regulated hydraulic regimes. In these systems, predictable effluent chemistry and controlled exchange processes enable *Salicornia* to serve as both a crop and a treatment component. As wastewater complexity increases, however, feasibility becomes conditional. Municipal and industrial matrices introduce heavy metals, pharmaceuticals, and other co-contaminants, necessitating rigorous monitoring and contaminant-aware biomass routing. Demonstrated metal and emerging contaminant uptake underscores that physiological tolerance does not eliminate the need for fate-resolved deployment.

A central conclusion of this review is that pollutant removal in *Salicornia*-based systems is frequently system-dominated rather than plant-dominated. Microbial transformations underpin much nitrogen and organic-load attenuation, substrates and sediments govern phosphorus retention and contribute to metal immobilisation, and harvest-mediated export provides only incremental salt reduction relative to loading rates. Consequently, *Salicornia* is most effective when embedded within hydraulically engineered treatment architectures that make sinks measurable and routing defensible.

When chemical characterisation, hydraulic design, microbiome function, and biomass routing are aligned within defined operational envelopes, *Salicornia* systems have considerable potential to contribute to circular and climate-resilient wastewater reuse in saline, coastal, and arid landscapes. However, broader implementation will require further long-term field validation, standardized reporting frameworks, complete nutrient and contaminant mass-balance studies, and techno-economic assessment to strengthen the evidence base and support safe, economically viable, and regulatorily robust deployment.

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Abbreviations

The following abbreviations are used in this manuscript:

AE100	100% aquaculture effluent
AE50	50% aquaculture effluent
APX	Ascorbate peroxidase
BADH	Betaine aldehyde dehydrogenase
BOD	Biochemical oxygen demand
BOD_5	Biochemical oxygen demand over 5 days
CAT	Catalase
COD	Chemical oxygen demand
CW	Constructed wetland
DIN	Dissolved inorganic nitrogen
DW	Dry weight
EC	Electrical conductivity
FO	Forward osmosis
FO-RO-FO	Forward osmosis-reverse osmosis-forward osmosis
FW	Fresh weight
GST	Glutathione S-transferase
HE	Hydroponic effluent
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
IMTA	Integrated multi-trophic aquaculture
NHX	Na+/H+ antiporter
OMWW	Olive mill wastewater
PGPR	Plant growth-promoting rhizobacteria
POD	Peroxidase
RAS	Recirculating aquaculture system
RO	Reverse osmosis
ROS	Reactive oxygen species
SNS	Standard nutrient solution
SOD	Superoxide dismutase
SOS	Salt overly sensitive
TDS	Total dissolved solids
TSS	Total suspended solids
V-PPase	Vacuolar H+-pyrophosphatase

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