



Technologies Available for Treatment of Saline Water for Livestock Drinking: A Review

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Water is an essential nutrient required for physiological and metabolic processes in livestock. However, in many arid and semi-arid regions, freshwater resources are scarce, and saline or brackish water becomes the only available source. Consumption of saline water can adversely affect livestock productivity and health. Desalination offers a solution by converting saline water into potable quality. This review explores the technologies available for desalination of saline water for livestock drinking, encompassing thermal, membrane-based, chemical, and renewable energy-assisted systems. Reverse osmosis (RO), electrodialysis (ED), multi-stage flash distillation (MSF),

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vapor compression distillation (VCD), and freeze desalination are examined in detail. Additionally, solar desalination and its potential for decentralized livestock farms is discussed. The review concludes by emphasizing the need for technology selection based on water quality, energy availability, scale of operation, and economic viability.

Keywords: Saline water; livestock; electro dialysis; thermoregulation; metabolism.

1. INTRODUCTION

Water is vital for sustaining life and productivity in livestock, impacting processes such as digestion, thermoregulation, metabolism, milk production, and waste excretion (Woodford et al., 1985). The water balance in the body is determined by the intake versus losses via sweat, milk, urine, feces, and respiration (Ahmed et al., 2000). Various environmental and dietary factors including temperature, wind, body size, and diet composition also influence water requirements. In regions affected by drought, salinity, or seawater intrusion, access to freshwater is increasingly limited, compelling farmers to rely on alternative sources such as saline or brackish groundwater (Gude, 2016). However, high salinity levels in water can result in reduced feed intake, poor growth rates, diarrhea, reproductive issues, and increased mortality (Zhou & Tol, 2005). However, in several parts of the world, especially arid and semi-arid regions, access to freshwater is limited. Saline water sources, often from groundwater or seawater intrusion, are not suitable for direct livestock consumption due to their adverse physiological effects (Gleick, 2000; Lattemann & Höpner, 2008). Thus, treating saline water is crucial for livestock sustainability in these areas. The efficiency and feasibility of desalination depend on several factors including water salinity level, available energy sources, livestock type, and economic considerations (Rizzuti et al., 2007). This review examines the various desalination technologies available for producing safe drinking water for livestock, along with their advantages, limitations, and suitability under different farming conditions.

2. WATER QUALITY STANDARDS FOR LIVESTOCK AND POULTRY

According to the National Academy of Sciences (1972), the salinity level of water significantly affects its suitability for different livestock species (Table 1).

3. BASICS OF DESALINATION

Desalination is the process of removing dissolved salts and other minerals from saline

water sources to render the water suitable for human consumption, agricultural use, and livestock drinking (Kalogirou, 2005). The theoretical minimum energy required to desalinate seawater is approximately 3 kJ per kilogram of water, as dictated by thermodynamic limits. However, practical desalination processes typically require significantly higher energy inputs due to system inefficiencies, frictional losses, and the need for pre- and post-treatment (Elimelech & Phillip, 2011; Karagiannis & Soldatos, 2008). This energy-demanding nature underscores the importance of optimizing desalination technologies for both energy efficiency and cost-effectiveness. Generally, there exists a trade-off between energy efficiency and capital expenditure in the design and operation of desalination systems.

Desalination technologies can be broadly categorized into three primary types based on the mechanism of salt removal:

- 1. Thermal Desalination:** This method involves phase change through evaporation and subsequent condensation. It is most commonly implemented through techniques such as Multi-Stage Flash (MSF) distillation, Multi-Effect Distillation (MED), and Vapor Compression (VC). These systems are energy-intensive but are robust and suitable for large-scale operations with high salinity input.
- 2. Membrane Desalination:** Membrane-based systems employ semi-permeable membranes to separate salts from water. The most widely used technique in this category is Reverse Osmosis (RO), which utilizes high-pressure pumps to force water through membranes that block salt ions. Other methods include Nanofiltration (NF), Electrodialysis (ED), and Forward Osmosis (FO). Membrane technologies generally require less thermal energy but depend heavily on electrical energy and require regular membrane maintenance.

Table 1. Water quality guidance for livestock and poultry (EC, dS/m)

EC (dS/m)	Rating	Livestock Suitability
<1.5	Excellent	Safe for all classes
1.5–5.0	Very Satisfactory	Safe; temporary diarrhea in unaccustomed animals
5.0–8.0	Satisfactory	Usable; may be refused or cause digestive issues
8.0–11.0	Limited Use	Avoid for pregnant/lactating animals; not suitable for poultry
11.0–16.0	Very Limited Use	Significant risk for most classes; only older animals may tolerate
>16.0	Not Recommended	Unfit for livestock use

3. Chemical Desalination: This approach involves chemical reactions such as ion exchange or chemical precipitation to remove salts from water. Although not as commonly used for large-scale desalination as thermal or membrane methods, chemical processes are useful for specific applications such as removing particular ionic species or softening water.

Each of these methods comes with its own set of advantages, limitations, and suitability depending on the quality of the feedwater, energy availability, and economic considerations. Continued advancements in materials science, process integration, and the use of renewable energy sources are driving innovation in this critical field of water treatment.

4. DESALINATION TECHNOLOGIES

4.1 Reverse Osmosis (RO)

Reverse Osmosis (RO) is currently the most widely implemented desalination technology for both brackish water and seawater treatment due to its high efficiency and modular scalability (Greenlee et al., 2009). The process involves applying high hydraulic pressure to force saline water through a semi-permeable membrane that selectively allows water molecules to pass while rejecting dissolved salts and other impurities. This pressure must exceed the osmotic pressure of the saline solution, particularly in the case of seawater, which typically requires pressures in the range of 55–80 bar.

A standard RO system comprises three main stages:

- **Pre-treatment:** This stage is critical for prolonging membrane life and ensuring consistent performance. It typically involves the removal of suspended solids through filtration, adjustment of pH to reduce scaling potential, dosing of anti-scaling and anti-fouling agents, and

disinfection (usually via chlorination followed by dechlorination) to control biological growth.

- **Membrane Separation:** The core of the RO system consists of membranes commonly fabricated from polyamide thin-film composites. These membranes are configured in various module formats, including spiral-wound, hollow fiber, and tubular designs. Spiral-wound modules are the most prevalent in commercial RO plants due to their balance of efficiency and cost.
- **Post-treatment:** After desalination, the permeate water is often low in essential minerals and slightly acidic. Therefore, post-treatment processes are employed to adjust the pH, add minerals for taste and health benefits (e.g., calcium and magnesium), and conduct a final disinfection step to ensure microbial safety during storage and distribution.

Advantages of RO Technology

- High salt rejection efficiency, typically greater than 99% for monovalent ions.
- Compact and modular system design, making it suitable for a wide range of applications from household units to large municipal plants.
- Scalability and flexibility in operation.

Limitations

- **Membrane Fouling:** RO membranes are prone to fouling from biological materials, scaling from inorganic salts, and clogging by particulates, all of which reduce performance and increase maintenance costs.
- **Energy Consumption:** The process is energy-intensive, especially when treating seawater, due to the high pressures required.

- **Feed Water Sensitivity:** The performance and longevity of membranes are highly dependent on the quality of feed water and the effectiveness of pre-treatment processes.

Ongoing research is focused on improving membrane materials, developing energy recovery systems, and integrating renewable energy sources to address these limitations and enhance the sustainability of RO desalination.

4.2 Electrodialysis (ED)

Electrodialysis (ED) is an electrochemical desalination process that utilizes ion-exchange membranes and an electric potential to selectively remove dissolved ionic species from water. In an ED system, feed water flows between alternating cation- and anion-exchange membranes placed within an electric field. Under the influence of the electric field, cations migrate toward the cathode through cation-selective membranes, while anions move toward the anode through anion-selective membranes. As a result, ions are concentrated in alternate flow channels (concentrate stream), while desalinated water is collected from the remaining channels (diluate stream) (Strathmann, 2010).

ED is particularly advantageous for treating brackish water or other sources with relatively low to moderate salinity, as its energy consumption is directly proportional to the salt content rather than the volume of water being treated. This makes it significantly more energy-efficient than pressure-driven processes like Reverse Osmosis when dealing with low salinity feedwater.

Advantages of Electrodialysis

- Lower energy requirements for desalinating low-salinity or brackish water.
- High recovery rates and flexibility in operation.
- Capability to selectively remove specific ions, which is useful for targeted water quality improvement.

Limitations

- Primarily effective only for ionic solutes; non-ionic contaminants such as organics, pathogens, or particulates are not removed.

- Membrane fouling and scaling can reduce performance and require regular maintenance.
- Less effective for high-salinity water like seawater due to increasing energy demands and osmotic limitations.

To enhance the operational lifespan and performance of ED systems, Electrodialysis Reversal (EDR) has been developed. EDR periodically reverses the polarity of the applied electric field, causing the migration direction of ions to alternate. This reversal prevents the long-term accumulation of scale-forming salts on the membranes, thereby reducing membrane fouling and cleaning frequency. The self-cleaning effect extends membrane longevity and improves process reliability, making EDR a favorable option for treating challenging brackish water sources or industrial effluents with high scaling potential.

ED and EDR technologies continue to evolve, with advancements focusing on membrane durability, improved energy efficiency, and hybrid configurations that integrate with other desalination or water treatment systems.

4.3 Thermal Distillation Methods

4.3.1 Multi-Stage Flash Distillation (MSF)

Multi-Stage Flash Distillation (MSF) is one of the most established thermal desalination technologies, widely used in the Middle East and other arid regions with abundant energy resources. The MSF process involves heating saline feedwater, usually to temperatures between 90–120°C, and then allowing it to flow through a series of chambers or stages maintained at progressively lower pressures. In each stage, a portion of the water "flashes" into steam due to the sudden pressure drop. This steam then condenses on heat exchange tubes, producing fresh water, while the remaining brine is passed to the next stage (Wade, 2001).

The process typically includes 20–30 stages to maximize freshwater yield and thermal efficiency. MSF is known for its operational robustness and ability to handle high-salinity and poor-quality feedwater, including industrial effluents and seawater with high scaling potential.

Advantages

- **Proven and mature technology** with decades of operational history in large-scale plants.
- **Highly robust** and capable of treating high-salinity or turbid water with minimal pre-treatment.
- **Stable output quality** with relatively low membrane or chemical dependency.

Limitations

- **High thermal energy consumption**, typically supplied through steam or waste heat, making it cost-inefficient where energy is expensive.
- **Scaling and corrosion issues**, especially at higher operating temperatures, requiring careful monitoring and chemical treatment.
- **Substantial infrastructure and operational costs**, making it less suitable for small-scale or decentralized applications.

4.3.2 Vapor Compression Distillation (VCD)

Vapor Compression Distillation (VCD) is another thermal desalination process that is particularly well-suited for small- to medium-scale applications, such as industrial facilities, ships, and remote communities. In VCD, vapor generated from boiling saline water is compressed using either mechanical (MVC) or thermal (TVC) compressors. The compressed vapor is then used as a heat source for further evaporation, making the process energy-efficient by reusing latent heat (Al-Karaghoul & Kazmerski, 2013).

This self-sustaining cycle allows VCD systems to operate with a relatively compact footprint and lower external heat input compared to MSF or MED systems. However, the performance of VCD is highly dependent on the reliability and efficiency of the compressor unit.

Advantages

- **Compact system design**, making it ideal for decentralized, remote, or portable installations.

- **Lower energy consumption** than traditional thermal systems, due to internal heat recovery through vapor compression.
- **Adaptable for integration** with renewable energy sources like solar or geothermal heat.

Limitations

- **High capital costs**, especially for mechanical compressors, which are complex and require precise engineering.
- **Significant maintenance demands** for the compressors, which are subject to mechanical wear and performance degradation over time.
- **Limited scalability**, making it less viable for large-scale municipal desalination projects.

4.4 Freeze Desalination

Freeze desalination, also known as freezing or cryogenic desalination, is a lesser-used but promising method based on the principle that when saline water is frozen, the resulting ice crystals exclude most of the dissolved salts. As the water freezes, pure ice forms, while the salts remain concentrated in the unfrozen brine. Once the ice is separated from the brine and melted, it yields desalinated fresh water (Nelson et al., 2005).

The process typically involves three main steps: controlled freezing of the saline water, separation of the pure ice from the saline concentrate, and melting of the ice to recover fresh water. Care must be taken during the freezing process to ensure that ice crystals do not trap significant amounts of brine, which would reduce the desalination efficiency. Separation is usually achieved through methods such as centrifugation or washing with cold fresh water.

Freeze desalination is a thermodynamically efficient process, especially at low ambient temperatures, because the latent heat of fusion required for phase change is lower than the latent heat of vaporization used in thermal methods. It is also inherently resistant to common issues like membrane fouling or scaling, as the process occurs at low temperatures.

Advantages

- **High water purity**: The resulting fresh water is of excellent quality, often requiring little to no post-treatment.

- **Low scaling and corrosion risk:** Operating at low temperatures reduces the risk of scale and corrosion, which are significant challenges in thermal desalination systems.
- **Potential integration with cold-climate or cryogenic waste heat systems,** improving energy efficiency in suitable environments.

Limitations

- **High capital cost:** The equipment required for controlled freezing, ice separation, and handling is complex and expensive.
- **Challenging solids handling:** Efficient separation and purification of ice crystals from the saline brine can be technically demanding, particularly in continuous or large-scale systems.
- **Energy consumption and system complexity:** Although thermodynamically efficient, practical implementations may involve considerable energy use due to refrigeration, unless integrated with waste cold or renewable sources.

Freeze desalination is currently under research and limited-scale deployment, particularly in regions with naturally cold climates or access to cryogenic energy sources. With further development, it holds potential as a niche or complementary solution in the broader desalination landscape, especially where high-quality water and minimal scaling are priorities.

4.5 Chemical Approaches

Chemical desalination involves the use of chemical reactions or selective chemical processes to remove dissolved salts and impurities from water. While not as widely applied as thermal or membrane technologies, chemical methods offer certain advantages in specialized contexts or when integrated into hybrid systems. These processes typically include ion exchange, gas hydrate formation, and chemical precipitation, each leveraging distinct mechanisms for salt removal (Ghaffour *et al.*, 2013).

4.6 Ion Exchange

Ion exchange is a well-established chemical treatment technique where dissolved salts are removed by exchanging undesirable ions in the water with more benign ions on a solid resin. Cation-exchange resins replace positive ions (e.g., Na^+ , Ca^{2+}) with hydrogen (H^+) or other desired cations, while anion-exchange resins replace negative ions (e.g., Cl^- , SO_4^{2-}) with hydroxide (OH^-) or other benign anions. When H^+ and OH^- are used, they recombine to form water, effectively deionizing the feed solution.

Ion exchange is highly effective for producing ultrapure water, especially in industrial applications such as electronics manufacturing or boiler feedwater treatment. However, it is not practical or cost-effective for treating seawater or highly saline sources due to the rapid exhaustion of exchange resins and the high frequency of regeneration required.

Advantages

- Produces high-purity, deionized water.
- Selective removal of specific ions.
- Effective in low to moderate salinity applications or as a polishing step.

Limitations

- Inefficient for high-salinity water due to rapid resin saturation.
- Requires chemical regenerants (acids and bases), creating secondary waste streams.
- High operational and material costs, limiting use to niche applications.

4.7 Gas Hydrate Separation

Gas hydrate desalination is an emerging technique that utilizes gas hydrate formation for salt separation. Under controlled conditions of low temperature and high pressure, gases such as methane, carbon dioxide, or propane can form crystalline hydrate structures with water. These hydrates typically exclude salts during formation. Once formed, the hydrate crystals can be separated from the brine and then decomposed to release fresh water and recover the gas for reuse.

While theoretically promising, gas hydrate separation remains at the experimental and pilot stage. Its commercial feasibility is constrained by

the need for precise temperature and pressure control, high equipment costs, and complex solid-liquid separation steps.

Advantages

- Low operating temperature reduces scaling and corrosion risks.
- Potential for integration with cold or cryogenic energy sources.
- Can produce very high purity water.

Limitations

- Technically complex and not yet commercially scalable.
- High energy input for pressure control and hydrate separation.
- Challenges in continuous operation and system control.

4.8 Precipitation Techniques

Precipitation-based desalination relies on inducing chemical reactions that precipitate specific salts or contaminants out of solution. This can be achieved by adjusting pH, adding chemical precipitants, or altering temperature to trigger the formation of insoluble salts. Once precipitated, the solids can be removed through sedimentation, filtration, or centrifugation.

This method is more commonly used as a pre-treatment or softening step, particularly to remove hardness ions like calcium and magnesium, which can form scale in downstream processes. It is not typically used for comprehensive desalination due to its limited efficiency in removing all dissolved salts and the high cost of chemicals.

Advantages

- Targeted removal of scaling agents or specific ions.
- Useful as a pre-treatment to protect RO membranes or thermal systems.

Limitations

- Inefficient for broad-spectrum desalination.
- Generates chemical sludge that must be managed or disposed of.

- High chemical consumption and operational costs.

5. RENEWABLE ENERGY IN DESALINATION

5.1 Solar Desalination

Solar desalination is increasingly viewed as a sustainable method, especially in off-grid or rural areas. Solar thermal collectors or photovoltaic (PV) panels power distillation or RO units.

Advantages: Low operating costs, environmentally friendly

Limitations: Intermittent operation, lower productivity.

Solar stills, solar-powered RO, and hybrid PV-thermal systems are under development for small-scale livestock applications (Tiwari *et al.*, 2003).

5.2 Wind and Geothermal Energy

Wind-powered RO systems and geothermal-assisted MSF are being explored for desalination, particularly in regions with relevant resources (Shatat & Riffat, 2014).

6. APPLICATION IN LIVESTOCK DRINKING WATER

Desalination technologies have great potential to improve water availability for livestock in saline-prone areas. RO is the most feasible technology due to its modularity and scalability. Electrodialysis offers promise for slightly saline water. For larger centralized systems, MSF and VCD provide high throughput. Freeze and solar desalination are promising for remote or cold climates.

Implementation must consider:

- Water quality and salinity level
- Scale and type of livestock operation
- Local climate and energy availability
- Cost and technical feasibility

7. CONCLUSION

Water scarcity remains one of the most pressing challenges facing livestock production in arid, semi-arid, and coastal regions, where conventional freshwater sources are often limited

or non-existent. In such environments, the reliance on saline or brackish groundwater becomes inevitable. However, unregulated use of saline water can have detrimental effects on animal health, including decreased feed intake, poor weight gain, digestive disorders, reproductive failures, and even mortality. Therefore, ensuring access to safe and palatable drinking water is a cornerstone for sustainable livestock management in these areas.

Desalination technologies offer a promising and increasingly necessary solution to mitigate the adverse effects of saline water on livestock. Among the various options, reverse osmosis (RO) and electrodialysis (ED) have emerged as the most practical and effective techniques for treating brackish water. These membrane-based processes offer high efficiency, scalability, and proven success in field applications. RO, in particular, is widely used for its excellent salt rejection capabilities and modular design, allowing it to be adapted to various farm sizes and water qualities.

For high-salinity or seawater sources, thermal desalination technologies such as multi-stage flash distillation (MSF) and vapor compression distillation (VCD) remain vital. Although these systems are energy-intensive, they are robust and capable of handling large volumes of saline water. They are best suited for centralized installations where infrastructure and energy supply are consistent. Freeze desalination, while still under research and limited in commercial deployment, shows promise for high-quality output with reduced scaling and corrosion problems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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