Desalination of brackish water for agriculture: challenges and future perspectives for seawater intrusion areas in Vietnam

Vo Huu Cong

ABSTRACT

This research aims to provide an overview of the seawater encroachment threat on agriculture in lowland areas and potential solutions for better practices. It was found that the Mekong river delta experiences severe impacts from climate change with more than 75% of provinces affected by seawater intrusion, of which Kien Giang, Ca Mau and Ben Tre provinces are the most influenced with 70% affected areas. The salinity of river water was observed in the range of 15–30 g/L in 2015; meanwhile, the strongest tolerated rice species reached ceiling values of 3–4 g/L. Emerging challenges were identified due to the uncertain upstream hydrological regime coupled with high levels of tide, field evaporation and water withdrawal. The development strategies of affected provinces are given on the modification of rice tolerant capacity, and modification to aquaculture in areas with high salinity, in which water purification is in urgent demand. Desalination technologies have been proposed with various innovations which are still not practical on a large scale. The desalination of seawater and brackish water by reverse osmosis, nano-filtration, electro-dialysis, ion-exchange resins, electrochemical processes and thermal distillation has been applied to agriculture. The advance reverse osmosis shows most potential because of its advances in treating performance, cost effectiveness and effective rejection of brine.

Key words | agriculture, brackish water, desalination, environmental risk, seawater intrusion

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INTRODUCTION

Salt stress causes a major threat to agriculture and severely impacts on agricultural production where seawater is used for irrigation (Bader *et al.* 2015). It causes a hostile environment for crop production as low organic matter content in soils, nutrient deficiencies of N and P, micronutrients such as Cu and Zn are both widespread (Alam *et al.* 2017). This threat is elevated in regions with low hydrological flow from upstream and high tide from downstream. The coastal and lowland provinces are dominated by rice cultivation but will eventually face damage due to drought and seawater intrusion. This situation has become a burning issue since large areas in the Mekong river delta (MRD), central highlands and south-central regions have declined in rice production in 2015. The Food and Agriculture Organization (FAO 2016) reported about 52 of the 63 provinces, more than 83% of the country, were affected by drought, with 18 provinces severely affected. In some regions, 60–90% of crops, corresponding to a total of 425,900 hectares of arable land, suffered badly. About 1.75 million people have lost income due to the influence of drought on the agricultural industry. This situation occurred in 1997 and 2002, affected approximately 4.3 million people and damaged 477,113 hectares of farmland. Therefore, advance risk reduction and prevention should be initiated to secure agricultural production and health.

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Vietnam is a developing country whose agricultural sector contributes roughly 16.32% of national gross domestic production (GSO 2017). Prevention of severe impacts from seawater intrusion on rice cultivation is one of the highest priorities. Innovations such as irrigation systems, reservoir systems and dike construction were implemented in the most vulnerable areas. However, recent variations of climate conditions have lowered the function of these initiatives, requiring further investment. The involvement of technological development to combat the impact of climate change has been studied worldwide. Vien & Cong (2015) indicated that reclamation of wastewater would be a potential water supply source for sustainable agricultural development. The research suggests that the water supply from re-utilization of industrial and domestic wastewater could be an alternative choice because discharge water quality meets an acceptable level. The merits of water reuse apply to those sectors that consume large amounts of water during operation. Desalination of seawater or brackish water for drinking water has been studied and commercially applied (Subramani & Jacangelo 2015); however, little is known regarding agricultural water supply (Burn *et al.* 2015). This study presents recent advantages, challenges and perspectives of brackish water desalination for seawater intrusion areas of Vietnam.

SEAWATER INTRUSION SITUATION

The United Nations (2016a, 2016b, 2016c) reported that acute drought and seawater intrusion have severely affected more than 1.75 million people in 18 provinces along the south of Vietnam, and encroached inland to an extent of 20–25 km. Salinity of river water was observed at 4.0 g/L at locations 38 km from the sea. In the Co Chien and Cái Lơn rivers, salinity levels were in the range of 10–30 g/L, reaching the highest level in 100 years (Figure 1). The unexpected high salinity occurring was due to the hydrological regime change combined with high tides.

Sewater intrusion occurred in most provinces with a coastline. Thang &Hien (2012) simulated salinity concentration for the Red river delta using MIKE 11 for scenarios until 2030, which showed an increase of 2–4 g/L compared to current conditions. The irrigation system in Thai Binh is highly vulnerable due to seawater intrusion directly onto the rice fields. Table 1 shows the constitutions of seawater in Hai Hau district, Nam Dinh province and Do Son district, Hai Phong Province. It contains various anions (Cl^-, SO_4^{2-}, HCO_3^{2-}, Br^-, H_3BO_3) and cations (Na^+, Mg^{2+}, Ca^{2+}, K^+), whereas Na^+ and Cl^- are dominant at 8.8–9.2 and 15.6–16.4 g/L, respectively.

The impact of seawater intrusion on rice was reported by the Water Resource Directorate (2016) (Table 2). As shown, ten provinces are particularly affected by seawater intrusion including Kien Giang, Ca Mau, Ben Tre, Bac Lieu, Soc Trang, Tra Vinh, Long An, Tien Giang, Vinh Long and Hau Giang. The affected area of seawater intrusion was separated into two categories including 70% coverage and 30–70% coverage areas. Kien Giang, Ca Mau and Ben Tre provinces are most affected with 34,093, 30,474 and

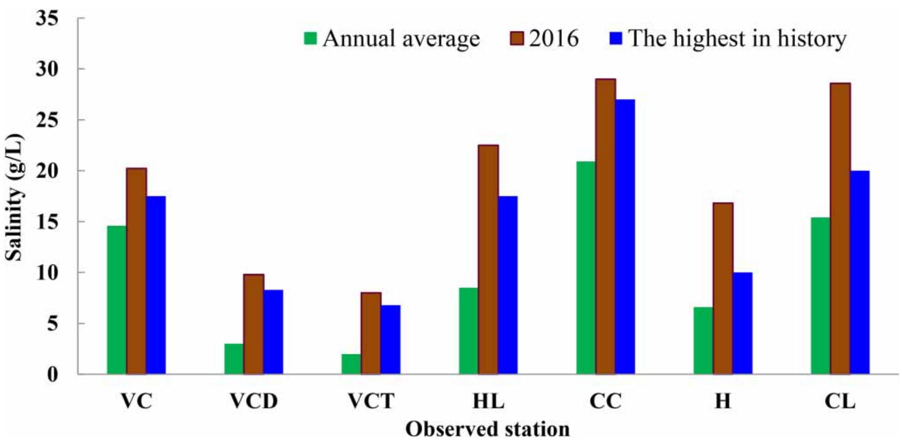

Figure 1 | Largest salinity to the end of February 2016 compared to annual average and cycle in regional history Mekong delta (VC: Vam Co river, VCD: Vam Co Dong river, VCT: Vam Co Tay river, H: Ham Luong river, CC: Co Chien river, H: Hau river, CL: Cái Lơn river). *Source:* Reproduced from SIWRR (2016).

Table 1 | Main composition of seawater in Hai Hau and Do Son district (g/L)

Location	Na^+	Mg^{2+}	Ca^{2+}	K^+	Cl^-	SO_4^{2-}	HCO_3^{2-}	Br^-	H_3BO_3
Hai Hau[a]	8.76	1.16	0.33	0.35	15.60	2.70	1.14	0.05	0.07
Do Son[a]	9.17	1.08	0.34	0.12	16.40	2.10	0.12	0.04	0.06
Seawater[b]	10.75	1.29	0.42	–	19.35	2.70	–	–	–
For agriculture[b] (mg/L)	<20	12–18	32–48	–	<20	>30	–	–	–

Sources: [a]Ha & Hoa (2011).
[b]Kumar *et al.* (2017).

Table 2 | Estimated risks for rice production caused by seawater intrusion

			Estimated affected area (hectares)	
No.	Province	Rice cultivation area (hectares)	> 70%	30–70%
1	Kien Giang	360,887	34,093	–
2	Ca Mau	120,959	30,474	17,101
3	Ben Tre	19,774	16,201	2,999
4	Bac Lieu	54,991	7,477	5,338
5	Soc Trang	213,559	5,406	4,534
6	Tra Vinh	67,430	2,939	2,116
7	Long An	234,851	2,161	6,490
8	Tien Giang	74,134	2,051	4,223
9	Vinh Long	44,435	179.9	1,095
10	Hau Giang	77,890	–	1,203

Source: Modified and reproduced from WRD (2016).

16,201 ha, respectively. Surprisingly, Ben Tre province is most vulnerable to seawater intrusion with about 97% of the rice cultivation area being affected (80% of the area for rice cultivation is severely affected by seawater intrusion). To cope with the severe impact of salinity, farmers turn their rice farms into aquaculture farms. This strategy seems better for brackish water areas but is still an immense problem for land affected by drought. Therefore, modification of the water supply for better practice of rice cultivation and aquaculture should be carefully considered.

DESALINATION TECHNOLOGIES IN AGRICULTURE

Desalination has become a familiar concept in the field of environmental engineering or water purification. The application of reverse osmosis (RO) for agricultural purposes was proposed in Europe in the 1960s. Despite the cost of desalted water remaining relatively high for agricultural irrigation, it is applied for high-value cash crops such as greenhouse vegetables (Ruíz–Garcia *et al.* 2016). Recently, large-scale desalination suitable for agricultural purposes has been generally achieved by thermal or osmotic based technologies and electrochemical processes (Duke 2015). This section describes recent developments in the desalination process for agricultural water supply.

Reverse osmosis

The motivation to use RO for desalination comes from the slogan 'making the desert green', initiated in the United States. However, the high purification costs of this technique made this unachievable at that time. In Europe, the Canary Islands (Spain) have taken the lead in desalination since 1960, having used intensive technologies as a means of providing water resources for agriculture (Ruíz–Garcia *et al.* 2016). The first RO plant for brackish water desalination was built in 1979 with a capacity of 20–21 m^3/h for a range between 4–15 g/L. In this period, 219 plants were budgeted for but only 15 plants were built. Since then, the Gaza Strip (Palestine) constructed the first RO plant for brackish water desalination in 1991 with a capacity of 45 m^3/h, while six brackish water desalination plants and one seawater desalination plant were built elsewhere (Mogheir *et al.* 2013). Recently, many countries consider desalinated water to be the main water source for agriculture. For example, Spain produces 1.4 million m^3/day (22% of which is used for agriculture); Kuwait produces 1 million m^3/day (13%); Italy 64,700 m^3/day (1.5%); Bahrain 620,000 m^3/day (0.4%); and Qatar 0.1% (Burn *et al.* 2015).

Unlike others, RO application is suitable for a wide range of salinity between 2.5 and 35 g/L (total dissolved solids, TDS) with various applications in drinking and agricultural supply (Burn *et al.* 2015). The recent advancements in RO research claimed the development of suitable membranes and efficient modules fulfilled cost effective quality water production for agriculture (Quist-Jensen *et al.* 2015). Owing to a lower TDS in brackish water, RO achieves its high performance in this feeding water; hence, membrane lifetime and high recovery efficiency are improved.

The main concerns in the application of RO are the costs of desalination, energy, operation, installation and civil works. Nowadays, RO plants are installed in over 125 countries (Service 2006), and there has been an overall decrease in the production cost of RO. The desalination cost varies based on the electricity cost of the country. The current cost for desalinated seawater is between US$0.50 and 1.0/$m^3$ (Ghaffour & Amy 2013). The energy cost represents 30–50% of the operating costs. Cabassud & Wirth (2003) reported that an energy consumption for seawater desalination can be obtained between 4 and 12 kWh/m^3. Obviously, the cost of desalinated water depends upon the cost of energy. Shaffer *et al.* (2012) demonstrated that the integrated FO and RO process has the potential to achieve stringent product water quality requirements while consuming less energy than a conventional seawater RO facility.

Nano-filtration

Nano-filtration (NF) is an effective pressure-driven membrane process using material with a pore size of between 0.5 and 1.5 nm. Unlike RO and ultra-filtration processes, NF operates not only under lower operation pressures, higher water fluxes, and lower investment but also with high rejection rates for scale formation divalent ions (Zhou *et al.* 2012). Recently, NF membranes have mostly been used for the softening and removal of organic compounds from surface and brackish water (Burn *et al.* 2015). In a practical situation, NF is combined with other processes for better treated water quality, operation costs and longer life time. A full-scale NF plant in Saudi Arabia demonstrates the results of treating 8.6 ML/day, where the hardness is reduced from 7,500 to 220 mg/L, TDS from 45,460 to 28,260 mg/L, rejection of sulfate up to 99%, and divalent cations by 80–95% (Eriksson *et al.* 2005).

Electrodialysis

Electrodialysis (ED) is a membrane separation process in which ions are separated through ion-exchange membranes driven by potential gradient (Burn *et al.* 2015). In ED systems, the cations and anions are transferred via a direct current electric field through ion-selective membranes. By applying a potential gradient across the electrodes, cationic species (Na^+, K^+, NH_4^+) migrate to the cathode while anion species (Cl^-, SO_4^{2-}, PO_4^{3-}) move towards the anode. To enhance the selective removal process, cation exchange (CEM) and anion exchange membranes (AEM) were embedded into the electrolytic system to allow only positive or negative charges to pass through and reject ions to provide purified water (Ortiz *et al.* 2005). Thanks to its advantages, ED is mainly used for brackish water purification to produce potable water with relatively low energy consumption (Valeró & Arbos 2010).

Ion exchange resins

Ion exchange (IX) is used for the purification, separation, and decontamination of aqueous and other ion-containing solutions with solid ion exchange resins. They are either cation exchangers or anion exchangers and can be regenerated by acid or alkali, respectively (Burn *et al.* 2015). Therefore, the IX depends on chemicals for regeneration. This is the greatest drawback to limit the application of IX application in the desalination process. However, the IX is very suitable for removing organic or inorganic ions that cause membrane fouling (Lipnizki *et al.* 2012), and has advantages in terms of low capital and operating costs, high water recovery (up to 99% in some applications), high quality product water, low volume of reject wastewater, simplicity of operation, low energy requirement, compact physical footprint and minimal civil works requirements.

CHALLENGES OF DESALINATION TECHNOLOGY IN AGRICULTURE

Operation cost

The investment, operation cost and treatment performance are the most important criteria for application of the desalination processes. Table 3 shows the costs and related indicators for RO, electrodialysis, ion exchange resins and electrochemical process. The operation costs of the above-mentioned processes are in the range of 0.5–2.9 US$/m^3. The lifetime of the product is 7–10 years, except in the case of ion exchange resins which is only two years. The rate of water recovery achieved is around 90%, with the lowest ratio belonging to the RO process. It suggests that reverse osmosis and electrochemical processes are suitable for brackish desalination in terms of cost effectiveness.

Feedwater quality

For agricultural water supply, feedwater of brackish water is usually provided via a well; thus, the quality of water becomes different to its original from rich sources such as rivers. Therefore, low TDS content would decrease fouling. For low salinity brackish water in the range of 2.5–3.0 g/L, commercial desalination products achieve the best removal and economic performance. However, when salinity approaches 10 g/L, the proposed processes appear to be ineffective or working with high chemical requirements, while the RO process still works effectively. Shaffer *et al.* (2012) proposed an integrated forward and RO system to improve water quality and reduce fouling of RO membrane.

Brine disposal

One of the challenges in desalination processes is brine discharge because an inappropriate discharge would cause serious environmental risks. The potential damage caused by reject brine to the environment includes eutrophication, pH fluctuation, proliferation of heavy metals in the marine environment and sterilizing characteristics of disinfectants, which can cause serious problems to habitats (Giwa *et al.* 2017). There are different reject brine management strategies, including brine minimization, direct disposal, or direct use.

Brine minimization can be implemented through membrane-based, thermal-based, and emerging technologies. In order to increase the recovery of fresh water through a secondary process and minimize the volume of reject brine obtained from these sources, sufficient scale removal from the brine needs to be carried out through pretreatment (Giwa *et al.* 2017). Chemical pretreatment is mostly used for the removal of scaling or inorganic fouling precursors such as Ca^{2+}, Mg^{2+}, Ba^{2+}, and Sr^{2+} from brine before secondary treatment. Gabelich *et al.* (2007) reported very high water recovery of 95% through chemical pretreatment. Electro-kinetic treatment and ion exchange have been used in recent times to achieve the softening of primary brine prior to secondary membrane-based brine treatment (Van Hege *et al.* 2002; Hocking 2006). Thermal-based minimization of brine volume is normally used to treat high salinity through mechanical or natural evaporation approaches (Giwa *et al.* 2016a, 2016b). Macedonio *et al.* (2011) reported a recovery factor of 75–88% in the presence of an anti-scalant, and brine discharge was restricted to 0.27–0.75% of the raw water fed to the system.

The consideration of '*a waste*' as '*a resource*' is also applied to brine from the desalination process. Reject brine can be a valuable resource for the production of mineral salts, metals, and valuable chemicals. Salt recovery from reject brine adds to the economic value of desalination processes (Kim 2011; Pérez-González *et al.* 2012).

Table 3 | Costs for technology application

Process	Investment cost ($/m^3)	Operation cost ($/m^3)	Life time (years)	Water recovery (%)	Reference
Reverse osmosis	1,627–2,543	0.5–1.0	5–7	65–75	Ghaffour & Amy (2013), Valero *et al.* (2011)
Electrodialysis	580–3307	1.01–2.85	7–10	80–90	Burn *et al.* (2015), Valero *et al.* (2011)
Ion exchange resins	1,718–5,643	0.92–1.22	2	90	Burn *et al.* (2015)
Electrochemical process	436–2487	0.76–2.14	8–10	90	Dao (2011)

CONCLUSIONS

This research presents the seawater intrusion in coastal areas and the Mekong river delta, Vietnam. It shows very high salinity content (10–30 g/L) in river water as far as 25 km inland. This is a threat to conventional farming systems where rice is dominant in most communities. Hence, local people are debating an alternative choice, either changing their strategies toward aquaculture production or the renovation of crop systems. For sustainable agricultural development, reclamation of brackish water is a suitable choice for water supply.

It was found that commercial desalination products for agriculture have rarely been initiated worldwide. Comparing the river water quality with current technologies, the advance RO process could be applied for seawater or brackish water for agriculture. In addition, desalinated water could be used for cash crops due to high water recovery rates and possible reutilization of reject brine as minerals, but high costs are involved.

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