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# Role of seawater air conditioning for food security in hot coastal deserts

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**Abstract**

Food security is a critical concern in warm, arid regions, such as the Gulf Cooperation Council (GCC) countries, where extreme temperatures, scarce freshwater, and limited arable land constrain agriculture. A major challenge in these regions is meeting the large cooling loads required for greenhouses, food storage, and related agricultural infrastructure. These cooling needs are typically met through evaporative cooling during winter months and high-tech, energy-intensive air-conditioned greenhouses during the summer, which are costly and associated with substantial $CO_2$ emissions. In this paper, we investigate Seawater Air Conditioning (SWAC)-powered food production and storage hubs for coastal, warm, and dry regions. SWAC uses naturally cold deep seawater, transferred through heat exchangers to chilled-water loops, to provide cooling. We focus on the techno-economic performance of SWAC systems, with particular attention to economies of scale and design cooling loads. Results for Oman show that, with 11 km of offshore pipelines, the levelized cost of cooling for SWAC plants with cooling capacities of 50 MWt and 2 GWt is 19.6 and 6.3 USD/MWht, respectively, which is substantially lower than those of high-tech air-conditioned greenhouses (29 USD/MWht) found in the region. SWAC provides low-carbon, renewable cooling that can support year-round controlled-environment agriculture, enhance grain and food cold storage, enable modern aquaculture, and improve

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meat and dairy production, offering a transformative pathway to strengthen food security while reducing the environmental footprint of food systems in the GCC and other warm coastal regions.

**Keywords:** seawater air conditioning, food security, desert agriculture, sustainable cooling, Gulf Cooperation Council, water-energy-food nexus.

## 1. Introduction

The Arabian Peninsula is experiencing rapid economic and population growth, requiring innovative approaches to ensuring food security (Bhattarai & Yousef, 2025). To date, this has relied heavily on diversified food imports (Odnoletkova & Patzek, 2023), which are subject to a range of trade disruptions, supply chain vulnerabilities, and price fluctuations. High ambient temperatures and severe heat during the summer months limit traditional forms of agricultural production (Sun et al., 2019). The hot and arid conditions, with limited fresh water and depleting groundwater, require novel approaches to improving domestic production (Qadir et al., 2007). High-tech solutions (e.g., high-tech greenhouses and indoor vertical farming) are high-cost and limited to a narrow set of crops (Suri, 2025). Addressing these multifaceted challenges necessitates the adoption of innovative, sustainable technologies that can overcome environmental constraints and enable resilient domestic food production and storage (Springmann et al., 2018).

The need for cooling permeates most aspects of food production, processing, and storage in hot climates (Alamri et al., 2023). Greenhouses, crucial for year-round fresh produce in deserts, require massive cooling inputs to maintain optimal growing temperatures and manage humidity, especially during the extreme summer temperatures (Zou et al., 2025). Grains stored in hot, humid conditions are susceptible to spoilage from respiration, mold growth, and insect infestation (El Melki et al., 2023). Maintaining cool, dry conditions is vital for preserving quality and extending the viability of strategic food reserves (Jayas, 2012). Meat, fish, dairy, fruits, and vegetables require continuous refrigeration from production and storage to consumption (Charles, 2025). High ambient temperatures increase the energy demand for these storage systems with cooling energy demand rising sharply during extreme-heat events and placing growing strain on urban energy systems (Yu et al., 2025). While some species

tolerate warmth, many high-value aquatic species thrive in cooler waters, and hatcheries require precise temperature control for optimal yields and survival rates (Islam et al., 2022). Many food processing operations, from chilling milk to preparing packaged meals, require controlled cool environments to maintain hygiene, ensure product quality, and ensure the comfort of workers and animals. The substantial energy demand for cooling across these sectors in GCC countries creates a significant economic and environmental burden, making a cost-effective and sustainable cooling solution essential for enhancing food security in warm regions (Khosla et al., 2021).

For example, Figure 1(a) illustrates a significant food security challenge for the Gulf Cooperation Council (GCC) countries, characterized by extreme external reliance, which compromises its food security, indicating a grains import dependency ratio of 70% or higher between 2021 and 2023. This heavy reliance on global markets is made more precarious by the data in Figure 1(b), which reveals that the GCC's strategic grain storage capacity is exceptionally low, barely visible on a scale where the USA and China maintain roughly 800 and 700 million tons, respectively. With storage capacity likely totaling less than 20 million tons for the entire region, the GCC faces a double-sided vulnerability: it is almost entirely dependent on foreign supply chains while lacking the physical reserves necessary to weather significant global shipping disruptions and sudden price spikes (Musa, 2025).

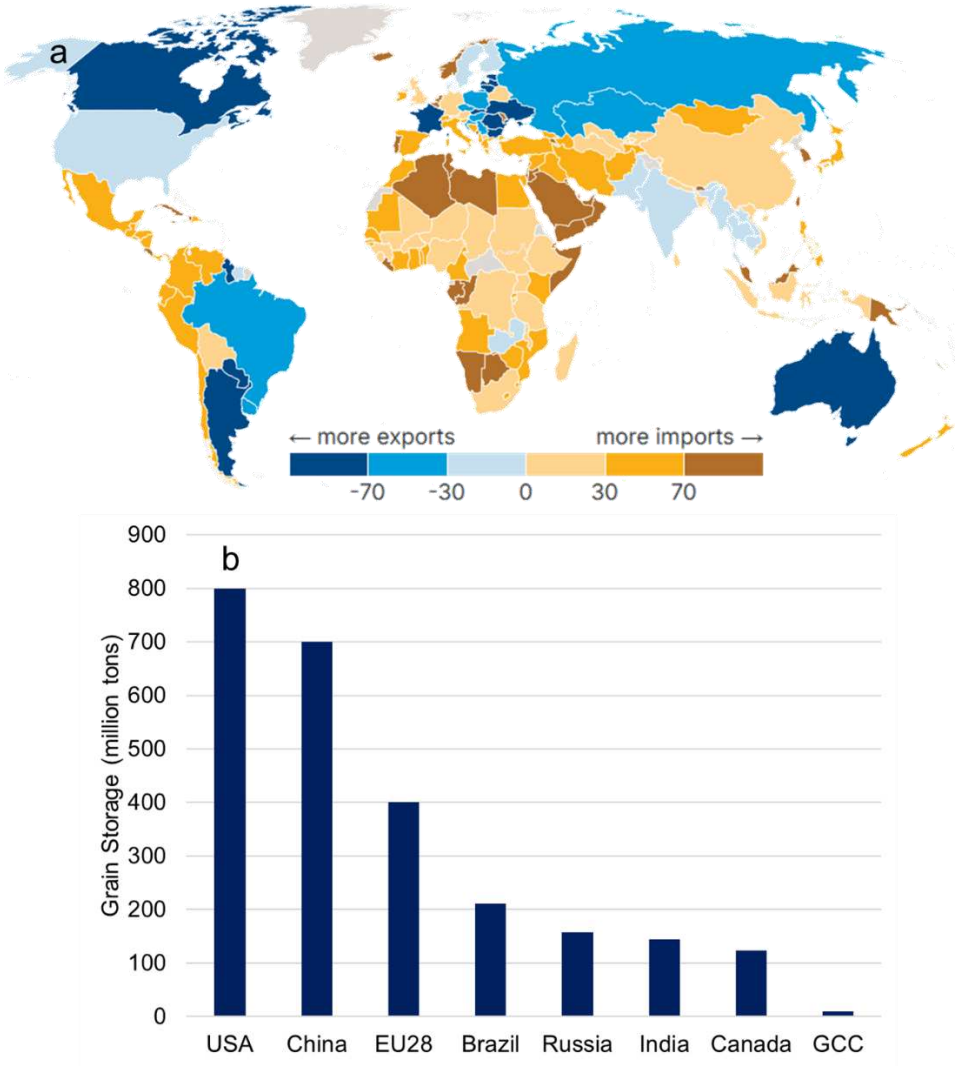
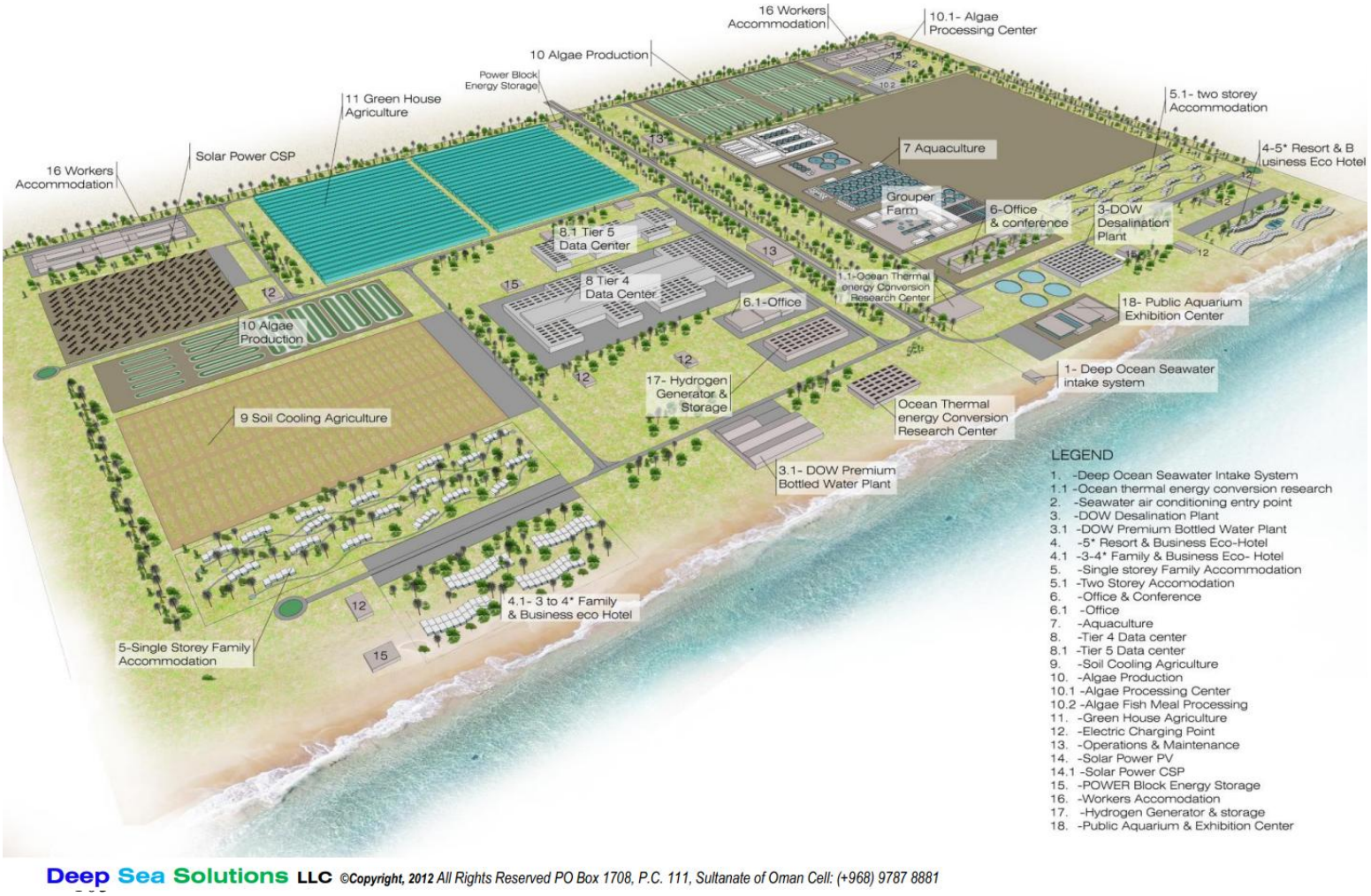



Figure 1: (a) Grains import dependency ratio in per cent from 2021 to 2023 (UN Trade and Development (UNCTAD), 2025) (b) grain storage comparison between different countries and GCC countries in 2023 (chinadaily, 2023; Miller Magazine, 2018; Munch, 2023).

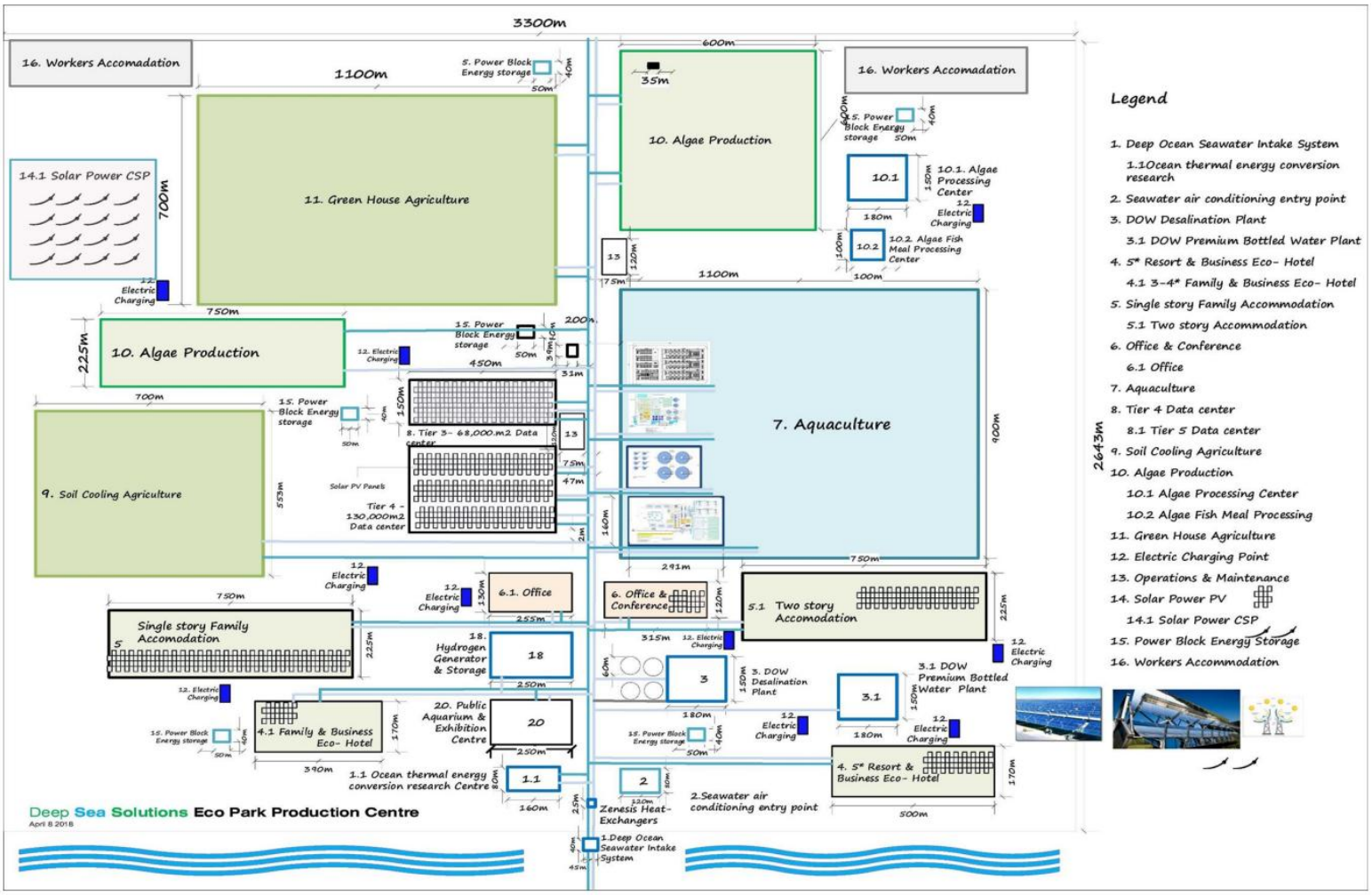
Seawater Air Conditioning (SWAC) is a cooling technology that harnesses the stable, low temperatures of deep ocean water, typically found at depths of around 900 meters (approximately 4°C to 7°C) (Hunt et al., 2021). A heat exchanger transfers this coolth from the deep seawater to a freshwater (Sanjivy, Raybaud, Marc, et al., 2026), ammonia (Hunt et al., 2022), or mobilized thermal energy storage (Hunt et al., 2025) district cooling system, which provides cooling to buildings, industrial processes, agricultural facilities, and storage sites. Compared to conventional vapor-compression cooling systems, which are electricity-intensive and rely on refrigerants, SWAC can reduce cooling energy consumption by up to 90%, resulting in substantial operational cost savings and significant

reductions in greenhouse gas emissions and peak electricity demand (Sanjivy, Raybaud, Hunt, et al., 2026). For instance, the 2.4 MWt SWAC plant in Tetiaroa reported overall COP values of 15 to 20 (Sanjivy et al., 2023), which is substantially higher than the COP of 3 in conventional ACs. Annual emissions were approximately 225 $tCO_2$ with SWAC, compared with 860 $tCO_2$ for conventional split systems. Centralized district cooling has been shown to substantially lower the carbon intensity of space cooling in cooling-dominated coastal regions, with techno-economic assessments reporting payback periods of under four years (Ayou & Eveloy, 2020). While successfully deployed in many applications globally, SWAC's potential for integrated food production and storage, from greenhouse cooling to cold chain logistics, remains largely untapped, particularly in hot, coastal desert regions where the demand for cooling is large (Hunt et al., 2019a).

The Sultanate of Oman possesses a distinct macro-geographical advantage within the Arabian Peninsula, defined by a 3,165 km coastline that drops precipitously into deep marine trenches (Katz & Alzeedi, 2026) with 5 to 7°C deep-sea water found at depths between 1000 and 1250 (Hunt et al., 2019b) accessible close to major cities and industrial and potential agricultural zones. Two recently published studies investigate the costs for SWAC in Oman. One investigates the use of shallow seawater for cooling and investigates the changes in surface water temperature in the Sea of Oman and the Arabian Sea (Hoseini Karani et al., 2026). The second paper proposes the use of deep seawater SWAC for resorts, data centers, agriculture, and aquaculture (Katz & Alzeedi, 2026), as shown in Figure 2 and Figure 3. Due to the large offshore pipeline required for SWAC projects in Oman (10-km offshore pipeline), the capital cost for the SWAC plant is estimated at 53 million USD to provide an average of 45 MW. However, combining the large gains in scale in SWAC plants costs and the huge demand for cooling for food production in GCC countries, we propose and investigate the use of SWAC for food production in hot and dry countries. We argue that SWAC costs would substantially reduce if it supplied a 2 GWt cooling demand (food production) instead of 45 MWt for cooling buildings. Similar gains in scale are observed in other engineering projects, such as pipelines (Kuby et al., 2011), hydropower, and pumped hydropower plants (Slapgard, 2012).




106 Figure 2: SWAC hub proposed by Deep Sea Solutions to Oman, side view (Katz & Alzeedi, 2026).




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Figure 3: SWAC hub proposed by Deep Sea Solutions to Oman, top view (Katz & Alzeedi, 2026).

This paper evaluates the technical and commercial feasibility of Seawater Air Conditioning (SWAC) configurations with very high cooling demand, up to 5 GWt. It shows the potential gains in scale of SWAC plants, particularly with the increase in diameter of the inlet pipeline. Such high and concentrated cooling demands exist with the construction of future coastal agricultural hubs in Oman. Integrating SWAC into food production and storage infrastructure could offer a sustainable and energy-efficient solution for food production and strengthening strategic grain reserves. This paper investigates this opportunity through a case study in Oman, a country with a favorable coastal geography, access to deep seawater, and a growing interest in becoming a logistics and food security hub for the Gulf Cooperation Council (GCC) countries. The study assesses the technical and economic viability of implementing SWAC-powered food production and storage hubs. In doing so, the paper contributes to

120 the literature on climate-resilient food storage and offers a novel approach for integrating this renewable
121 cooling energy source into national food security strategies.
122
123 **2. Methodology**
124
125 The proposed SWAC food hub for hot deserts is presented in Figure 4a. It depicts a self-
126 contained ecosystem where a central SWAC plant, located on the coastline, draws in cold deep seawater
127 via an offshore pipeline and uses it to provide cooling to various food-related facilities. The warm return
128 water is discharged via an offshore pipeline. The hub is designed to maximize the benefits of coastal
129 access for SWAC. The proposed food hubs include food production (e.g., greenhouses, meat and dairy
130 farms, and aquaculture), food processing (chilling, packing, and manufacturing), and storage (grain
131 storage, cold rooms, and refrigerated warehouses). It receives chilled water (blue arrow) from the
132 SWAC plant to maintain low temperatures in the food hub's operations. For instance, greenhouse
133 plantations, essential for controlled-environment agriculture in the desert, receive chilled water to
134 maintain optimal growing temperatures year-round, thereby overcoming the extreme ambient heat in
135 the region and enabling efficient indoor farming (Allali et al., 2025). Meat and dairy farms receive
136 chilled water for animal comfort and to chill milk. Omani dairy farms typically require ambient
137 temperatures of 24 to 26°C, which requires mechanical cooling systems and large annual electricity and
138 maintenance costs. Deep seawater contributes to increased growth rates in abalone & oysters because
139 of its high levels of nutrients and minerals. Cold water is used for temperature control in tanks for
140 aquaculture. Grain storage facilities receive chilled water from the SWAC plant. This cooling is critical
141 for maintaining grain quality, preventing spoilage, inhibiting pest growth, and reducing respiration
142 rates, which are particularly important for long-term food security reserves (Xu et al., 2023). The SWAC
143 plant acts as the central provider of cost-effective, sustainable cooling.

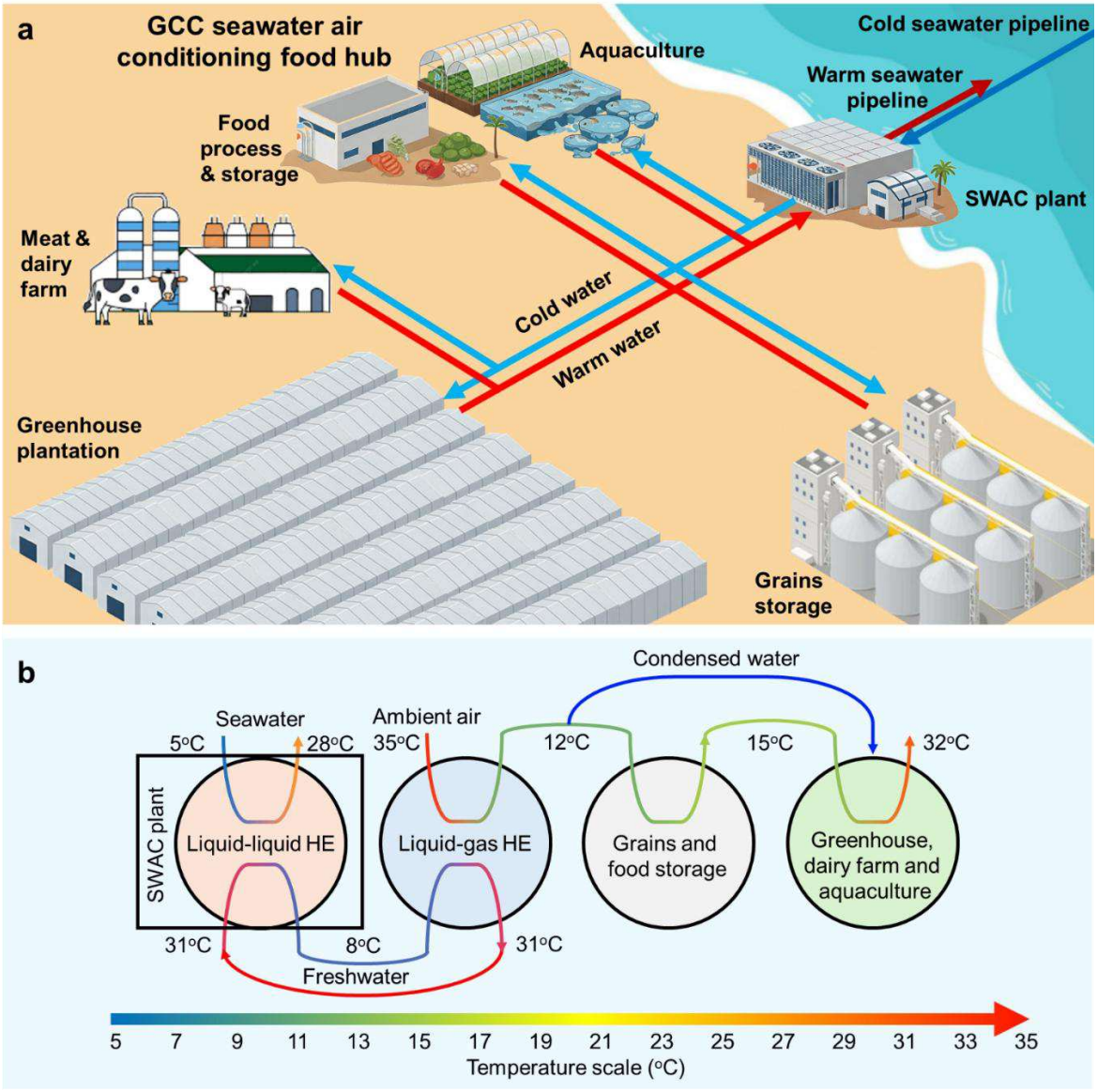



Figure 4: Proposed seawater air conditioning food hub in warm regions. (a) Top view layout of the food hub, (b) process flow diagram of the SWAC food hub.

The SWAC food hub's heat exchange and cooling demands processes are presented in Figure 4b. Seawater at 5°C exchanges heat with freshwater and returns to the sea at 28°C. The freshwater is used to cool the ambient air from 35 to 12°C. We assume a temperature difference of 3°C for liquid-liquid heat exchangers, with higher heat transfer coefficients, and 4°C for liquid-gas heat exchangers, with lower heat transfer coefficients. The air is then further cooled directly with a liquid-gas heat exchanger to lower the air temperature to 9°C. This lower temperature is suitable for storing cool grains, which can be stored for up to 2 to 3 years under these conditions. These low temperatures can be used to reduce electricity consumption for storing food (such as vegetables, fruits, meat, and fish) and for

freezing food. The cold air coming from the storage facilities is used to cool greenhouses, dairy and meat farms, and then aquaculture production. Other examples of high cooling demand in warm regions include data centers, airports, transportation logistics hubs, refrigerated warehouses, tourism and hospitality (hotels, resorts, and large event venues), hospitals, and industrial cooling.

To evaluate the performance and feasibility of the SWAC system, the following governing equations were utilized to determine the cooling load, pumping power requirements, and the overall Coefficient of Performance (COP). Equation 1 calculates the cooling capacity provided by the SWAC system as a function of the mass flow rate of the seawater and the temperature differential between the intake and discharge. Equation 2 calculates the electrical power required to drive the seawater pumps based on the total dynamic head the system must overcome. Equation 3 calculates the coefficient of performance (COP), i.e., the efficiency of the SWAC system, defined by the ratio of thermal cooling energy provided to the electrical energy consumed. Equation 4 calculates the head loss within the high-density polyethylene (HDPE) intake and outfall pipelines, which is a critical factor in determining pumping energy. It is calculated using the Darcy-Weisbach equation, which is favored for its accuracy across different flow regimes. The friction factor ($f$) is estimated with Swamee-Jain, Equation 5, for HDPE pipes, which are characterized by low surface roughness ($\varepsilon \approx 0.0015$ mm) in the turbulent regime. It depends on the Reynolds number, which is described in Equation 6.

$$Q_{cooling} = \dot{m}_{sw} \cdot c_p \cdot \left(T_{return} - T_{supply}\right) \tag{1}$$

$$P_{pump} = \frac{\rho_{sw} \cdot g \cdot \dot{V} \cdot H_{total}}{\eta_{pump} \cdot \eta_{motor}} \tag{2}$$

$$COP_{SWAC} = \frac{Q_{cooling}}{P_{pump} + P_{aux}} \tag{3}$$

$$h_f = f \cdot \frac{L}{D} \cdot \frac{v^2}{2g} \tag{4}$$

$$f = \frac{0.25}{\left[log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \tag{5}$$

$$Re = \frac{\rho_{sw} v D}{\mu} \tag{6}$$

Where, $Q_{cooling}$ is the cooling power (in kW), $\dot{m}_{sw}$ is the mass flow rate of seawater (in kg/s), $c_p$ is the specific heat capacity of seawater equal to 3.99 kJ/ kg K, $T_{return}$ and $T_{supply}$ are the seawater supply (5°C) and return (28°C) temperatures, respectively, which results in a 23°C temperature difference. $P_{pump}$ is the electrical pumping power (in kW), $\rho_{sw}$ is the seawater density assumed to be 1028 kg/m³, $g$ is the acceleration due to gravity, equal to 9.81 m/s², $\dot{V}$ is the volumetric flow rate (in m³/s), $H_{total}$ is the Total Dynamic Head (in m), comprising static lift and friction losses, $\eta_{pump}$ and $\eta_{motor}$ are the pump and motor efficiencies, respectively. $COP_{SWAC}$ is the overall coefficient of performance of the SWAC plant, $P_{aux}$ represents the auxiliary power consumption (e.g., distribution pumps, secondary loops). $h_f$ is the head loss due to friction (m), $f$ is the Darcy friction factor (dimensionless), $L$ is the length of the pipeline (m), $D$ is the internal diameter of the pipe (m), $v$ is the flow velocity (m/s). $\varepsilon$ is the pipe roughness height (m), $Re$ is the Reynolds number, μ is the dynamic viscosity of the seawater (Pa·s). A 20% thermal loss in the inlet offshore pipeline, heat exchanger, pumps, and distribution system is also assumed.

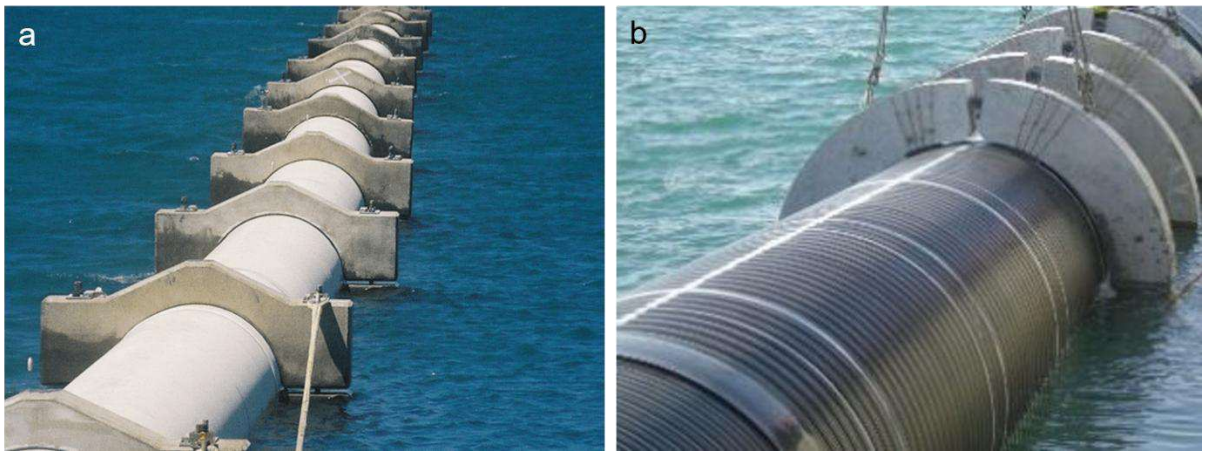
As this paper intends to describe a SWAC project with huge cooling demand to cool down food production in hot deserts, such as Oman, the methodology focuses on investigating the maximum viable gains in scale that can be reached with SWAC with the intent of minimizing the cooling costs for desert agriculture. This is performed by investigating the change in unit costs of the four main SWAC components with the increase in cooling demand of the plants. Table 1 describes in detail the component design of a large-scale SWAC plant offshore pipeline. Figure 5 presents the main change in design proposed in this paper, which is to replace Solid-wall HDPE (Figure 5a) with Structured-wall HDPE (Figure 5b). This paper selects structured-wall HDPE for the construction of large SWAC plants as it can reach 5 meters diameter in offshore applications.

Table 1: Large-scale SWAC components design.

| SWAC component | Options | Benefit |
|---|---|---|
| Offshore Pipeline | Solid-wall HDPE (3 m diameter) | Solid-wall HDPE is the cheapest and most practical option for offshore pipelines under 2.5 m diameter. It is immune to saltwater corrosion and biofouling-induced degradation. However, diameters larger than 2.5 m substantially increase its unit cost. Until now, all existing SWAC plants have been built using solid-wall HDPE. |

| | | |
|---|---|---|
| | Structured-wall HDPE (5 m diameter) | Structured-wall HDPE pipelines use hollow, ribbed, or corrugated profiles wrapped spirally (such as Krah or Weholite profiles). Structured-wall design uses 40 to 60% less raw material than solid-wall alternatives while retaining geometric rigidity and can reach up to 5 m diameter in maritime applications. Another advantage of Structured-wall HDPE pipes is that they are more flexible and easier to bend than solid-wall HDPE pipes. This significantly facilitates the installation of the SWAC pipelines, and the dredging required in the deep-sea bottom. This is particularly interesting for long pipelines, such as the one proposed for the Oman food hub. |

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194

195 Figure 5: (a) Solid-wall HDPE (Makai Ocean Engineering, 2026) and (b) structured-wall HDPE

196 (Krah, 2026) applications in offshore engineering.

197 To estimate the gains in scale of SWAC projects, it is important to assume unit costs for
198 different plant sizes. Figure 6 presents the unit costs for offshore pipelines, seawater and freshwater
199 pumps, heat exchangers and district cooling systems. These unit cost estimates are based on the author's
200 experience and the following references (Hunt et al., 2025; Katz & Alzeedi, 2026; Makai Ocean
201 Engineering Inc, 2015; State of Hawaii Department of Business, 2026). Figure 6a presents the change
202 in offshore pipeline costs with pipeline diameter. The cost varies from 4.2 to 13.2 M USD/km with the
203 increase in pipeline diameter from 1 to 5 meters, respectively, including pipeline manufacturing,
204 logistics, welding, ballasting, bathymetry screening and marine installation. The increase in diameter
205 increases the seawater flowrate in the pipeline more than the power of two (Equation 4). This reduces
206 the offshore seawater transportation cost from 6.42 to 0.38 USD/(km.m$^3$/s) with the increase in pipeline
207 diameter from 1 to 5 meters, respectively, which results in a 17 times reduction in price. Figure 6b
208 presents the change in seawater and freshwater pump cost with the pumped flowrate. A wet well (sump)
209 configuration is assumed, where the cold seawater flows naturally under gravity into an excavated

seawater tank. The seawater is then pumped from the tank into the heat exchanger with a vertical mixed-flow pump with a 35 meters pumping head. The cost varies from 1.6 to 55.6 M USD/km with the increase in seawater flow from 1 to 100 $m^3/s$, respectively, including pump, motors, electrical equipment, connection to the grid, 10 meters of excavation, building, access, contractor, engineering, and contingency. This reduces the seawater pumping cost from 1.64 to 0.56 USD/($m^3/s$) with the increase in flowrate from 1 to 100 $m^3/s$, respectively, which results in a 3 times reduction in price. The change in cost in the freshwater pump is similar to the seawater pump, and split-case centrifugal freshwater is used.

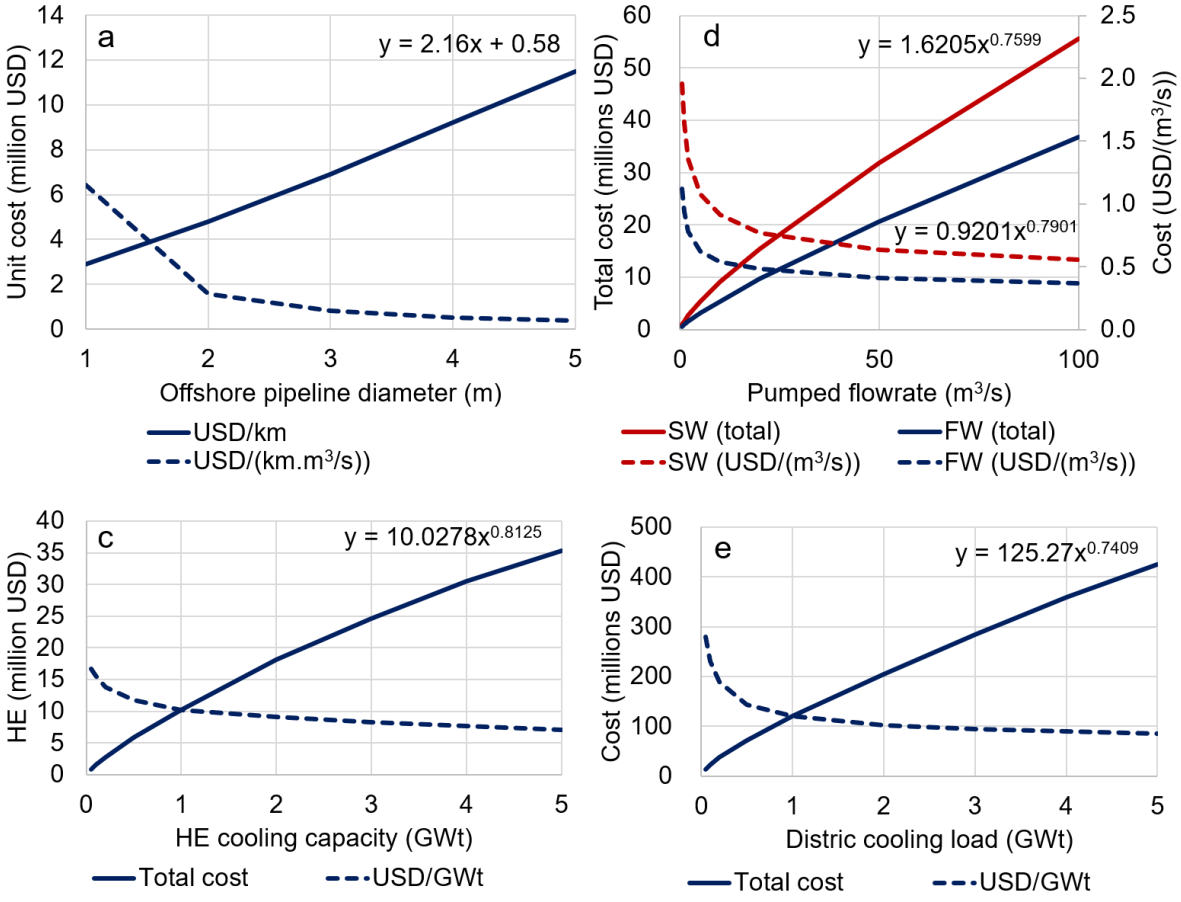



Figure 6: SWAC plan unit cost for (a) offshore pipeline, (b) seawater (SW) and freshwater (FW) pumps, (c) heat exchanger (HE), and (d) district cooling system.

Figure 6c presents the change in heat exchanger costs with cooling capacity. The cost varies from 0.84 to 35.4 M USD/km with the increase in cooling capacity from 0.05 to 5 GWt, respectively, including titanium plates heat exchanger, pipes, engineering, procurement and construction costs. The cost per cooling capacity varies from 16.7 to 7.1 USD/(km.$m^3/s$) with the increase in cooling capacity

from 0.05 to 5 GWt, respectively, which results in a 2.4 times reduction in price. Figure 6d presents the change in district cooling costs with cooling capacity. The cost varies from 14 to 425 M USD/km with the increase in cooling capacity from 0.05 to 5 GWt, respectively, including excavation, two-way pipelines, engineering, procurement and construction costs. The cost per cooling capacity varies from 280 to 85 USD/(km.m$^3$/s) with the increase in cooling capacity from 0.05 to 5 GWt, respectively, which results in a 3.3 times reduction in price. Table 2 presents the SWAC component cost reduction with gains in scale. It shows that the inlet and outlet offshore pipeline costs are the ones that change the most with gains in scale from 0.05 to 5 GWt cooling capacity.

221 Table 2: SWAC component cost reduction with gains in scale from 0.05 to 5 GWt cooling
222 capacity.

| SWAC components | Cost reduction with gains in scale |
|---|---|
| Inlet and outlet offshore pipeline | 17 |
| Seawater pump | 3.0 |
| Freshwater pump | 2.6 |
| Heat exchanger | 2.4 |
| District cooling system | 3.3 |

223

224

225 **3. Results**

GCC countries' access to deep seawater with temperatures below 5°C is mapped in Figure 7a, using ocean temperature data from [13]. It shows that only Oman can develop SWAC projects in the GCC region and that the depth to reach below 5ºC is between 1,500 and 1,750 m. The increase in depth to reach 5ºC seawater is due to the higher salinity of the seawater from the Red Sea and Arabian Gulf. Figure 7b presents a geographical analysis of potential SWAC offshore pipeline lengths required to access seawater at 5°C or lower along the northeast coast of Oman, near Muscat. The yellow arrows represent the estimated pipeline lengths required to connect coastal locations to depths of 5°C or less, with distances marked at 20 km intervals. The model used to assess the potential for SWAC grain storage in the GCC region is described in detail in (Hunt et al., 2019a), which uses bathymetric data of the world's oceans from (Weatherall et al., 2012). An interactive map highlighting potential locations for Seawater Air Conditioning (SWAC) projects in Oman, focusing on sites with pipeline lengths of

less than 30 km is presented in (Hunt, 2025). The SWAC plant with the shortest offshore pipeline length in the region is 11 km (Figure 7c). The data visualized in this figure and the interactive map help identify optimal locations for implementing SWAC systems that could support food production and storage activities. Figure 8 presents the temperature and salinity profile of the proposed Oman case study, with data from (National oceanic and atmospheric administration, 2018). As the temperature at 1,500 m depth is 5.40°C and the temperature at 1,750 m depth is 4.26°C, we estimate that the depth to reach 5°C is 1,510 m depth. With these temperatures, salinities, and 1,510 m depth, a 2.1 hydraulic head is required to overcome the higher density of the cold deep seawater inside the SWAC inlet pipeline. Even though the Red Sea reaches a depth of 3,040 m, its deep seawater is around 20ºC because the maximum depth of the Strait of Bab-el-Mandeb is 310 m, which does not allow dense, cold, deep water to enter the Red Sea (Agulles et al., 2020), as shown in Figure 9. The Arabian Gulf's maximum depth is 93 m, which also does not provide access to cold, deep seawater.

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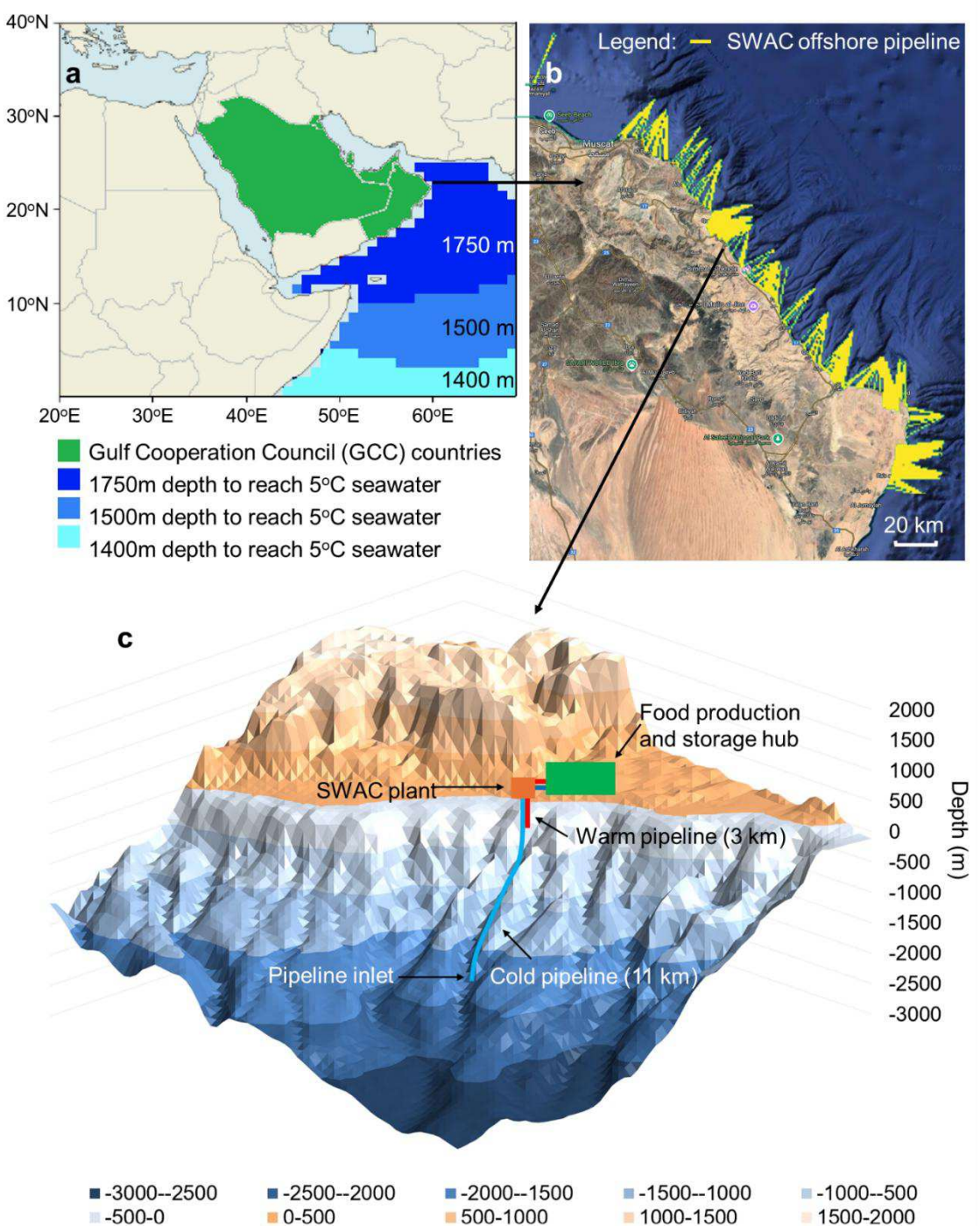
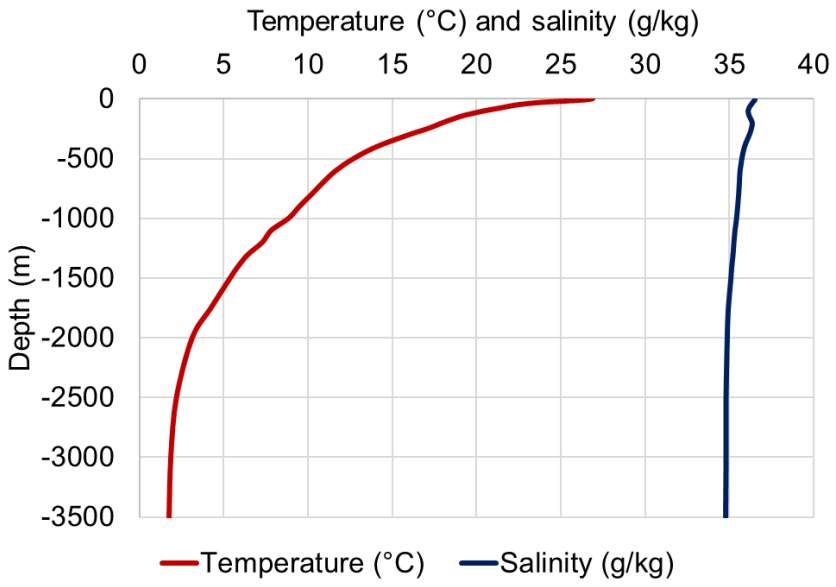



Figure 7: Potential for SWAC in GCC countries. (a) GCC countries' access to 5°C deep seawater and the required depth, (b) Oman's northeast coast, highlighting the shortest pipelines to reach deep seawater with temperatures below 5°C, (c) the proposed SWAC food hub in Daghmar, including the surrounding topography and bathymetry.




232

233 Figure 8: Temperature and salinity profile of the proposed Oman case study (National oceanic and
234 atmospheric administration, 2018).

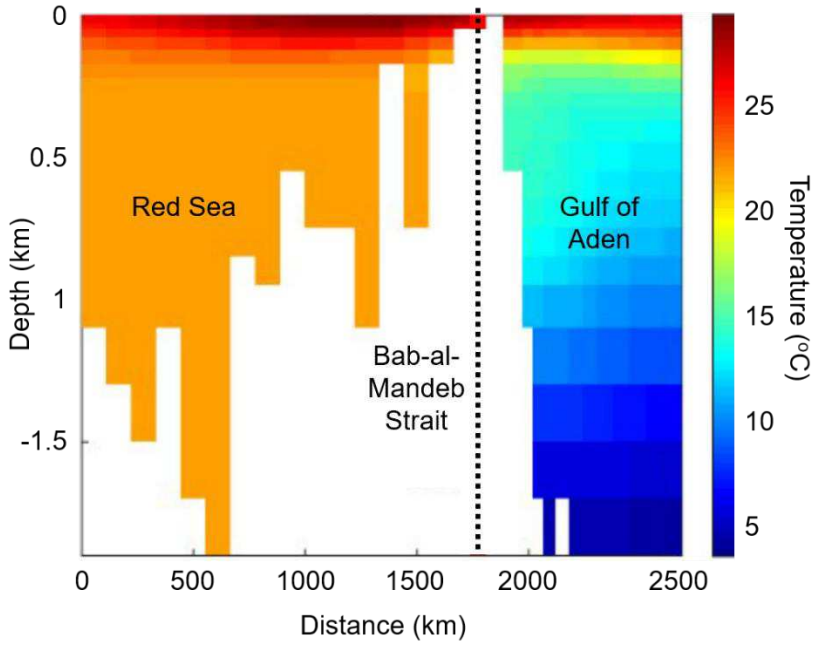



Figure 9: Deep ocean temperature profile in the Red Sea and Gulf of Aden (Agulles et al., 2020).

Figure 10a presents the SWAC cost variation with cooling capacity. The total cost of the SWAC plant varies from 0.92 to 964 million USD with the increase in cooling capacity from 0.05 to 5 GWt, respectively. The cost per cooling capacity varies from 966 to 193 million USD/GWt with the increase in cooling capacity from 0.05 to 5 GWt, respectively, which results in a 5 times reduction in price. The cooling cost lowers significantly while the capacity reduces from 0.05 to 2 GWt. However, from 2 to 5

GWt the cooling cost does not reduce substantially. This is because at 2 GWt the inlet and outlet offshore pipelines reach 5 m diameters. To reach 3 GWt cooling, it would require two inlet and outlet pipelines with smaller diameters. Figure 10c presents the SWAC plant components cost distribution. It shows that at low cooling capacities (0.05 GWt), the inlet and outlet offshore pipeline costs consist of 65%. This is because the pipeline is 11 km long, which is quite long for a SWAC project. The cost share of the offshore pipelines is reduced to 37% with a cooling capacity of 2 GWt, but then the cost slightly increases with a further increase in cooling capacity. Figure 10d presents a cooling cost with SWAC of 193 million USD/GWt with a cooling capacity of 2 GWt, which is used for the food hub proposed in Oman.

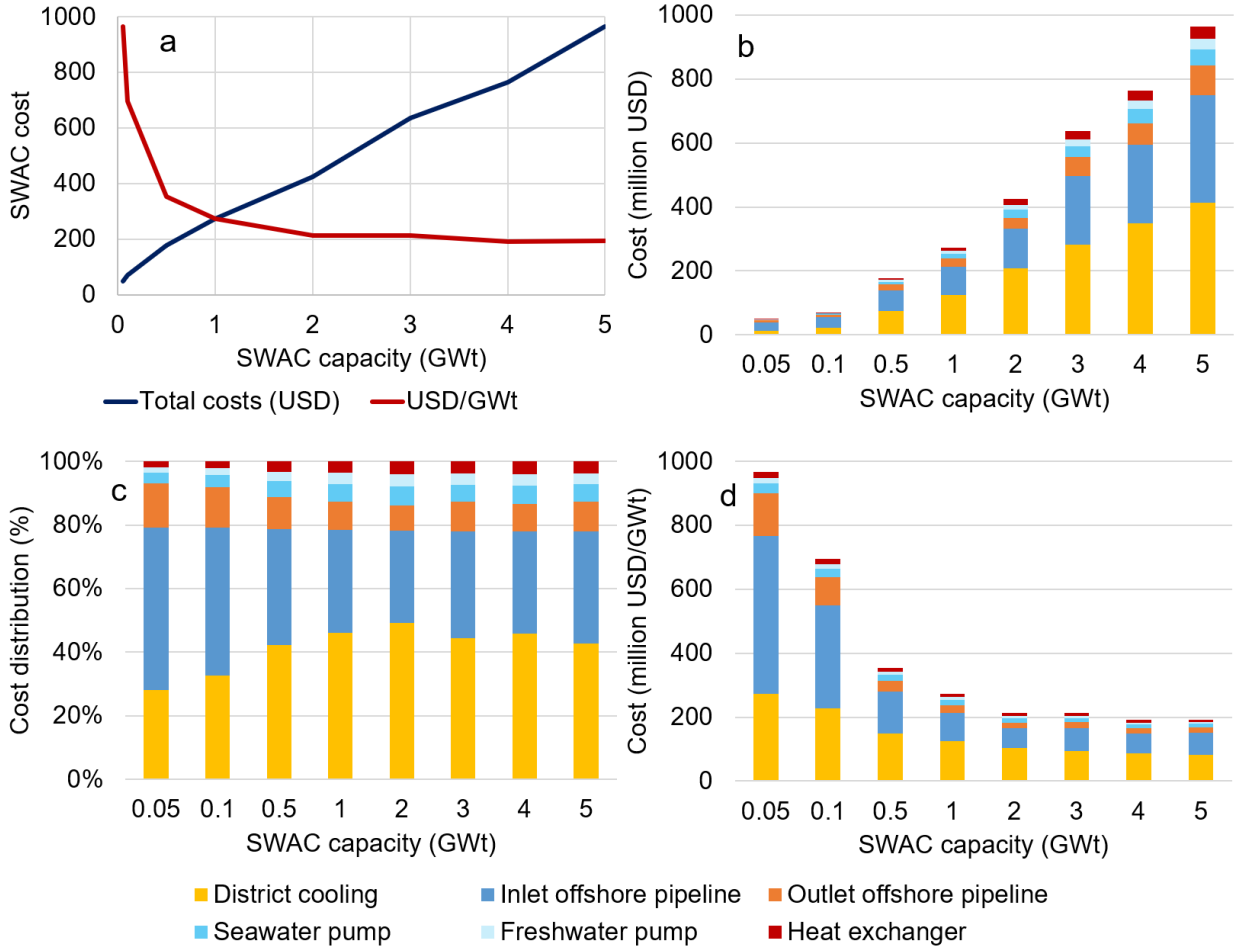



Figure 10: SWAC cost variation with cooling capacity presented as (a) scattered graph (total cost and USD/GWt), (b) column chart (component costs in million USD), (c) column chart (component cost distribution), and (d) column chart (component costs in million USD/GWt).

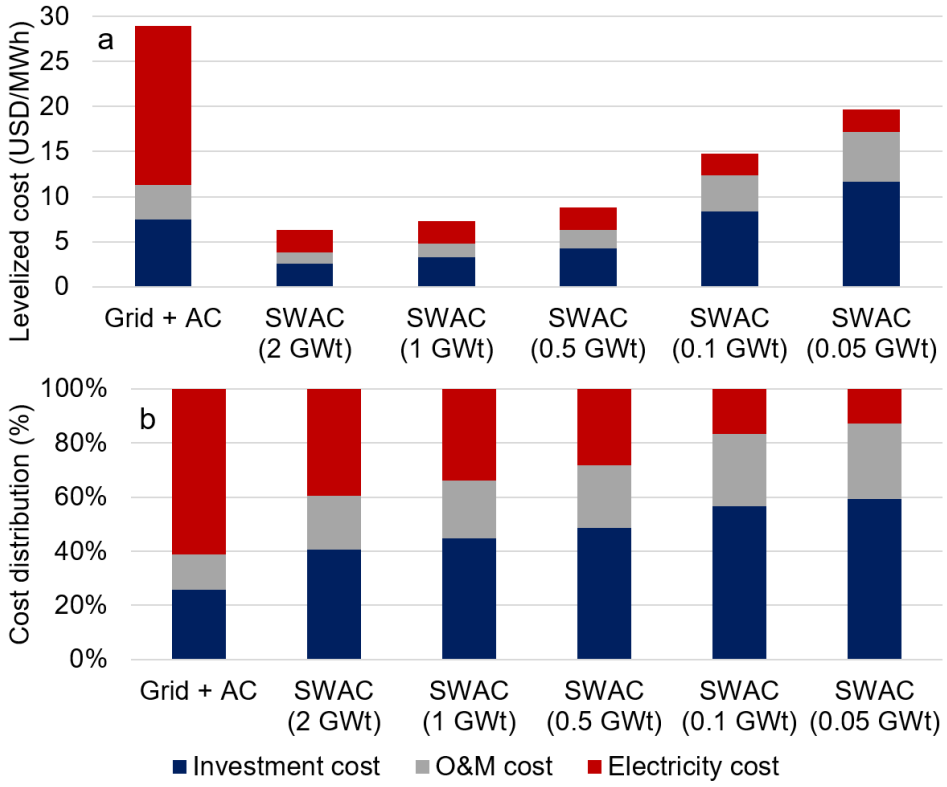
Table 3 and Figure 11 compare the costs described in Figure 10 with the cost for cooling greenhouses in Oman using grid electricity and an air-conditioning system. It shows that the levelized cost for SWAC with 2 and 0.05 GWt is 4.6 and 1.5 times lower than using grid electricity and AC. The investment and electricity consumption costs of SWAC with 2 GWt are 2.9 and 7.1 times lower compared with grid electricity and AC, respectively.

235 Table 3: Cost comparison between grid electricity and mechanical air conditioning and SWAC.

| Parameters | Grid + AC | SWAC (2 GWt) | SWAC (1 GWt) | SWAC (0.5 GWt) | SWAC (0.1 GWt) | SWAC (0.05 GWt) |
|---|---|---|---|---|---|---|
| Electricity costs in Oman (USD/MWh) | 62 | | | | | |
| Interest rate | 6% | | | | | |
| AC power cost (USD/kWt) | 450 | - | - | - | - | - |
| AC system (GWt) | 2 | - | - | - | - | - |
| AC investment cost (M USD) | 900 | - | - | - | - | - |
| AC O&M (M USD/year) | 40 | - | - | - | - | - |
| SWAC power cost (USD/kWt) | - | 212 | 272 | 354 | 695 | 966 |
| SWAC system (GWt) | - | 2 | 1 | 0.5 | 0.1 | 0.05 |
| SWAC investment cost (M USD) | - | 424 | 272 | 177 | 69 | 48 |
| SWAC O&M (M USD/year) | - | 13 | 8.17 | 5.31 | 2.08 | 1.45 |
| Lifetime | 20 | 50 | | | | |
| Discount factor | 11.47 | 15.76186064 | | | | |
| Coefficient of performance | 3.5 | 25 | | | | |
| Capacity factor | 0.6 | | | | | |
| Annual cooling production (TWt) | 10.52 | | 5.26 | 2.63 | 0.53 | 0.26 |
| Annual electricity consumption (TWh) | 3.00 | 0.42 | 0.21 | 0.11 | 0.02 | 0.01 |
| Annual electricity cost (M USD) | 186.21 | 26.07 | 13.03 | 6.52 | 1.30 | 0.65 |
| Millions of tons of CO2 per year | 1.44 | 0.21 | 0.11 | 0.053 | 0.011 | 0.005 |
| Levelized cost of cooling (USD/MWt) | 28.95 | 6.27 | 7.31 | 8.77 | 14.82 | 19.64 |

236 * Assuming 1 MWh from the grid emits 500 kg of $CO_2$.

237




238 Figure 11: Cost comparison between grid electricity and mechanical air conditioning and SWAC,
239 showing (a) the levelized costs and (b) the cost distribution of the levelized cost.

To validate these cost estimates presented in this paper, we compare the levelized cost for cooling proposed for the 45 MW Shangri-La Hotel and Sustainable City in Oman of 19 USD/MWh (Katz & Alzeedi, 2026) with the estimated levelized cost for cooling in this paper of 19.6 USD/MWh for a SWAC plant with 50 MW cooling capacity. We cannot validate the levelized costs of cooling for SWAC with higher cooling demands because such cooling capacities have not yet been built, and we could not find any technoeconomic analysis in the industry and literature. The estimated COP of 25 is consistent with the measured seasonal global COP of 24.7 at the Tetiaroa installation and is therefore reasonable as a central pre-feasibility value (Sanjivy et al., 2023). Nevertheless, extrapolating this performance from an operating 2.4 MWt system to a 2 GWt food hub remains a major source of uncertainty. Overall COP depends not only on the offshore intake pipeline, but also on pump heads and efficiencies, heat-exchanger effectiveness, chilled-water distribution distance and thermal losses. The levelized cooling costs reported in the present study should therefore be interpreted as a pre-feasibility scale-up scenario. The seawater intake temperature should likewise be treated as a design variable rather

than as a fixed boundary condition. A warmer intake could substantially reduce the offshore pipeline length and associated marine construction costs, particularly for higher-temperature applications (Sanjivy et al., 2024). A multi-temperature distribution architecture could therefore reserve the lowest-temperature loop for strategic food storage, while using warmer return flows for greenhouses, dairy and livestock facilities, and aquaculture. Future optimization of the Oman hub should jointly consider intake temperature, pipeline length and diameter, heat-exchanger approach temperatures, secondary-network temperature regimes, humidity-control requirements, and the temporal profiles of the different agricultural cooling loads.

## 4. Discussion

While the economic advantages of SWAC are evident, it is crucial to consider the broader implications of its implementation. The initial infrastructure costs, including the installation of offshore pipelines and SWAC plants, are substantial, particularly, given that no SWAC plant with cooling capacity higher than 50 MW has been implemented. Additionally, the discharge of colder seawater from the SWAC system into the surrounding environment could potentially lower local water temperatures, which may impact marine ecosystems if not properly managed. The region could mitigate this issue, as it has experience with the discharge of brine from desalination plants. To mitigate this impact, measures such as temperature-controlled discharge can be implemented, where the warmed water is gradually mixed with cooler surface waters before being released. Also, buffer zones and monitoring programs can be established to track temperature fluctuations and ensure that local ecosystems, including coral reefs and marine life, are not adversely impacted by the discharge. The integration of water treatment systems to remove contaminants before discharge can further reduce ecological harm. By implementing these mitigation strategies, SWAC can continue to support sustainable aquaculture without compromising the health of local marine environments.

From a systemic policy perspective, integrating SWAC systems into national planning frameworks addresses a critical vulnerability within the GCC's agricultural supply chain. With regional food retail waste valuations due to rapid shelf-life degradation in extreme heat, establishing low-cost

thermal storage zones can stabilize wholesale supply structures. Furthermore, considering that the GCC imports most of its food, deploying localized, SWAC-enabled food cultivation provides a realistic pathway to lower import dependencies. Also, with a cheap source of renewable cooling from SWAC plants, GCC countries can reliably hold grain reserves for 2 to 3 consecutive years without facing mass insect infestations or thermal degradation. This improves the water–energy–food nexus, in which one resource carries significant trade-offs and co-benefits for the others (Engström et al., 2017). These strategies directly support Oman's Vision 2040 milestones and the overarching national commitment to hit net-zero emissions by 2050.

Site feasibility is not governed by bathymetry alone, but by the interaction between seawater source temperature, pipeline length, end-use temperature requirements, and humidity control. Global mapping has shown that increasing the intake temperature from the conventional 5°C to approximately 12°C, when combined with high-temperature district cooling, can substantially shorten marine pipelines and expand the number of eligible coastal locations, including Oman (Sanjivy et al., 2024). Similarly, optimization of the Tetiaroa system indicated that an intake temperature of approximately 8°C could reduce marine infrastructure requirements while maintaining thermal comfort and adequate dehumidification (Sanjivy, Raybaud, Marc, et al., 2026). For food-production hubs, these findings suggest a differentiated design in which the coldest seawater is reserved for grain storage and refrigerated facilities, while progressively warmer secondary loops supply greenhouses, livestock facilities, and aquaculture. Such a temperature cascade could reduce capital expenditure and avoid the unnecessary use of high-quality cooling for applications with moderate temperature requirements.

Apart from cooling the ambient air, the SWAC plant also produces water by condensing the humidity from the air. This water can be used in the food hub’s greenhouses. For instance, assuming an average summer temperature of 35°C and 67% humidity at latitude 23.20 and longitude 58.97 (Open-Meteo, 2025), the air is cooled to 12°C and the total seawater cooling demand from the SWAC plant is 2 GWt. This results in a water production of 0.5 $m^3/s$, 42,285 $m^3/day$, or 7.6 million $m^3$ of water in six months. Comparing the electricity consumed to condense this water, which is around 0.42 TWh, the amount of electricity to condense the water is 55 $kWht/m^3$. Note, however, that this is substantially

higher than the electricity required to desalinate seawater, 3 kWh/$m^3$. Thus, water production should only be considered a by-product of the SWAC food hub.

## 5. Conclusion

The implementation of Seawater Air Conditioning (SWAC) in the food production and storage sectors offers significant benefits for food security in the Gulf Cooperation Council (GCC) countries, particularly in Oman, where the coastal geography is favorable for SWAC deployment. By harnessing the natural cooling power of deep seawater, SWAC systems can reduce reliance on conventional, energy-intensive cooling technologies, providing a cost-effective and sustainable solution for food storage, processing, and production. One of the most compelling advantages of SWAC is its potential to drastically lower energy consumption in food-related cooling applications. The GCC region, where high temperatures and high humidity pose substantial challenges to food preservation, requires extensive refrigeration for grain storage, cold chain logistics, and food processing. By using cold deep seawater to provide cooling to facilities such as grain silos, aquaculture farms, and greenhouses, SWAC reduces the need for traditional refrigeration systems, resulting in lower operational costs and reduced carbon emissions. The ability to offer cooling at a fraction of the cost of conventional air conditioning systems could play a pivotal role in improving food security in Oman and the GCC countries. As global food security concerns intensify, particularly in the face of climate change, innovative solutions like SWAC could play a pivotal role in transforming food systems, enabling countries to meet their domestic food needs while minimizing environmental impact.

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