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Industrial microbiology of solar salt production

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Solar salterns can be modeled as giant outdoor chemostats, much like a series of dams on a slow-moving river. Microorganisms and their products play an essential, but sometimes uncharacterized, role in salt production in these ponds, from seawater salinity up through NaCl saturation. They may physically affect the evaporation process and their by-products may chemically modify or bind with dissolved ions. Many solar salt facilities engage microbiologists to establish monitoring programs for analyses of nutrients, standing crop and associated biological variables in the ponds. Other solar salt companies engage microbiologists only when there are ''crises'' in the ponds that interfere with salt production.
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Introduction

The fields of industrial microbiology and solar salt production may seem antithetical, as salt is generally regarded as a bacteriostatic agent. However, it is generally accepted in the solar salt industry that microorganisms and their products in the evaporating ponds can affect both the quantity and quality of salt that is eventually produced. Many solar salt companies employ biologists to monitor biological development and associated parameters in the saltern ponds from the seawater inlets through the crystallizer ponds. Some companies engage consulting microbiologists only when problems occur in the ponds. The intent of this article is threefold: to describe how solar salterns work; to describe the roles of microorganisms in solar salterns; and to describe some of the analytical methods for measuring biological and chemical parameters that we have adapted to overcome problems of salt interference.

Solar saltern models

Solar salterns can be modeled as flow-through pond systems with distinct biogeochemical attributes associated with each pond and at each salinity [10,11]. Hence, they have some attributes of semi-closed chemostats. In a typical coastal solar salt facility, seawater is pumped into a series of shallow (typically $\leq$0.5 m depth) evaporating ponds. The high surface-to-volume ratio promotes evaporation as the brines slowly flow to each succeeding, more saline pond in the series. The intent of this form of brine management is to allow precipitation of the less soluble marine minerals (primarily $CaCO_3$ and $CaSO_4{\cdot}2H_2O$ [gypsum]) so that only NaCl precipitates in the crystallizer ponds. Most of the Ca^{2+} precipitates as gypsum, which forms a hard crust on the floors of those ponds. Gypsum begins to precipitate when seawater is concentrated about 4.5-fold. Once seawater has evaporated >90% of its water and nearly all the Ca^{2+} has precipitated, NaCl begins to precipitate. At this point, the brines are pumped to crystallizer ponds. As the brines continue to evaporate and much of the NaCl crystallizes, more soluble potash minerals (various minerals containing Na^+, Mg^{2+}, K^+, Cl^- and $SO_4{}^{2-}$) begin to precipitate. Unless potash minerals are desired, these brines (''bitterns'') become waste materials.

Distinct biological communities can be found throughout the system [10]. As seawater (3.5% salinity) concentrates about two-fold, the flora and fauna are typically those found in euryhaline estuaries. As seawater concentrates further, the fauna is dominated by the filter-feeding brine shrimp, *Artemia* sp., which is broadly halotolerant throughout most saltern systems. It is likely limited in distribution at the lower salinities by grazing fish, and at higher salinities by a variety of environmental factors (e.g., the metabolic cost of osmoregulation in strong brines, elevated brine temperatures and low oxygen levels). The flora is dominated by moderately halophilic (up to about 15% salinity) and extremely halophilic (up to NaCl saturation, >25% salinity) or halotolerant microorganisms. Most physiological or phylogenetic groups of bacteria can be identified from either the moderately or extremely halophilic salinity ranges including phototrophs (cyanobacteria and phototrophic bacteria), chemoautotrophs (sulfur-oxidizing bacteria) and heterotrophs (aerobes, anaerobic fermenters, sulfate reducers, nitrate respirers). Among the archaea, methanogens and halobacteria can be isolated. Among the eukaryotic algae, diatoms are typically found in the moderately halophilic range, but the most common algae are usually the wall-less green algae *Dunaliella viridis* and *D. salina*. The intense coloration of crystallizer ponds is due to the carotenoids of planktonic populations of halobacteria (red bacterioruberin) and *D. salina* (orange β-carotene). The trained eye of a saltern microbiologist can usually determine whether or not *D. salina* is present simply from the hue of the ponds.

Modeling the microbial development in solar saltern ponds and the influences of microbes and their products on salt production requires an interdisciplinary approach. It involves classical microbiology (microscopy and physiology), environmental microbiology (sewage waste treatment and marine microbiology), sedimentology, geochemistry and engineering. The following

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discussion describes some of the attributes in these giant outdoor chemostat systems.

"Good" and "bad" microorganisms and their activities

Typical concentrations of nutrients and microbial standing crops are shown in Table 1. A biogeochemical model of solar salterns is presented in Figure 1. This model integrates the essential roles of nutrient concentrations, salinity, sediment composition, phytoplankton load, microbial mat development, zooplankton grazers and dissolved organic carbon. Saltern managers often want to know if microorganisms are "good" or "bad" for the salt-making process. Based on measured and observed phenomena, we have developed an evaluation of microbial processes that may help or hinder the evaporation and crystallization processes.

Microbial mats are usually found in ponds of salinities high enough to exclude bottom-grazing animals, and below those of gypsum saturation. A typical microbial mat has a surface layer of cyanobacteria, which overlies a layer of phototrophic bacteria, which in turn overlies a community of fermenters, sulfate reducers and other anaerobic bacteria. Some nutrients that feed the mats are likely derived from the overlying brines. However, the compact mats are likely efficient recycling ecosystems that serve to maintain the mat community. Pinckney and Paerl [20] found significant nitrogenase activity in a hypersaline (7.4% salinity) microbial mat. Olson *et al* [17] described microbial mats as among the most dynamic N-limited habitats in the marine environment.

Microbial mats do not develop on the surface of thick gypsum crusts in the gypsum ponds. However, they can develop beneath gypsum crusts [3] upon soft sediments, which they use as sources of nutrients and trace elements to maintain the dynamic C, N and S cycle processes of these microbial communities. Caumette *et al* [3] did an extensive study of microbial processes in saltern mats beneath gypsum crusts, including diurnal profiles of oxygen and sulfide, and calculations of sulfate reduction rates. They found exceptionally high rates of sulfate reduction (average value of 8200 nmol cm^{-3} day^{-1}), which were comparable to rates measured by Canfield and DesMarais [2] in microbial mats in another saltern. In contrast, sulfate reduction rates are rarely found to exceed 1000 nmol cm^{-3} day^{-1} in normal marine environments, which may be sulfate-limited.

Microbial mats in salterns built on calcium carbonate sediments (e.g., old reef deposits) tend to be more poorly developed than those built on silicoclastic or volcanic sediments, presumably because fewer trace minerals can be extracted from $CaCO_3$. The same phenomenon can be observed in terrestrial vegetation surrounding the solar salt facilities.

The distribution of halobacteria and *Dunaliella* in the crystallizer ponds is dictated by nutrient concentrations. Halobacteria are heterotrophs that thrive on the dissolved organic carbon that passively increases by concentration as the water flows downstream to the crystallizers [10]. *D. salina* is a photoautotroph. In low-nutrient (oligotrophic) salterns, *D. salina* is entirely absent. In very oligotrophic salterns, halobacteria are also absent. In those cases, the saltern managers add a green dye (Solavap) to the crystallizer ponds to decrease the albido and aid evaporation. In some salterns, *D. salina* may be present for part of the year but absent at the end of the summer when nutrients are exhausted.

Microorganisms are considered "good" for solar salt production when there are moderate concentrations of nutrients in the system. Under these conditions, microbial mats help seal the concentrator ponds. Brine shrimp graze on planktonic algae and help clarify the concentrating ponds from excessive turbidity. The development of microorganisms producing carotenoids in the crystallizers is desirable because they aid in solar absorption.

Microorganisms are considered "bad" for the saltern under certain conditions. Under eutrophic conditions, many of the biological problems that are well known in freshwater ponds and lakes probably occur in saltern ponds. For example, dense populations of planktonic algae and bacteria that develop in the concentrator ponds shade the bottom and may prevent mats from forming. These dense planktonic blooms may cause anaerobic conditions to develop at night or on warm, windless, summer days. Such conditions appear to cause microbial mats (or stands of eukaryotic algae or sea grasses in lower salinity ponds) to lift from the bottom and float on the surface as rafts. As a result, there is a decrease in evaporation and an increase in odors from putrefaction and sulfate reduction, which are problematic for salterns built near communities. To the author's knowledge, oxygen, sulfide and volatile amines and organic acids have not been monitored in "problem" saltern ponds, nor have standard remedial methods (e.g., aeration) been tested to mitigate the problems.

It is also possible that the low redox conditions that accompany the activity of sulfate-reducing bacteria in eutrophic concentrating

Table 1 Typical concentration ranges of biological factors in oligotrophic and eutrophic saltern ponds

	Oligotrophic			Eutrophic		
	Pre-gypsum ponds	Gypsum ponds	Crystallizer ponds	Pre-gypsum ponds	Gypsum ponds	Crystallizer ponds
Salinity [°Bé]	3–15	15–25	26–30	3–15	15–25	26–30
Ammonia [μM]	0–7	0–7	0–7	1–50	1–50	5–50
Phosphate [μM]	0	0	0–2	0.3–20	1–10	2–60
Carbohydrates [mg/l]	<10	10–20	10–40	0–20	25–60	≥100
Turbidity [OD 400 nm]	≤0.050	≤0.020	≤0.030	0.010–>0.400	140–0.250	0.200–0.400
Particulate protein [mg/l]	<0.4	<0.4	<0.4	<1–7	4–15	20–35
Chlorophyll *a* [μg/l]	0–30	0	0	2–100	2–70	15–90
Sediment P [μg/g]	≤500	–	–	150–>1000	–	–
Sediment percent organic C	3–5% no mat 10–15% mat	–	–	2–16%	–	–

From Refs. [8–10]. °Bé is approximately equivalent to percent salinity below 26°Bé. Net turbidity measurements exclude intake brines.

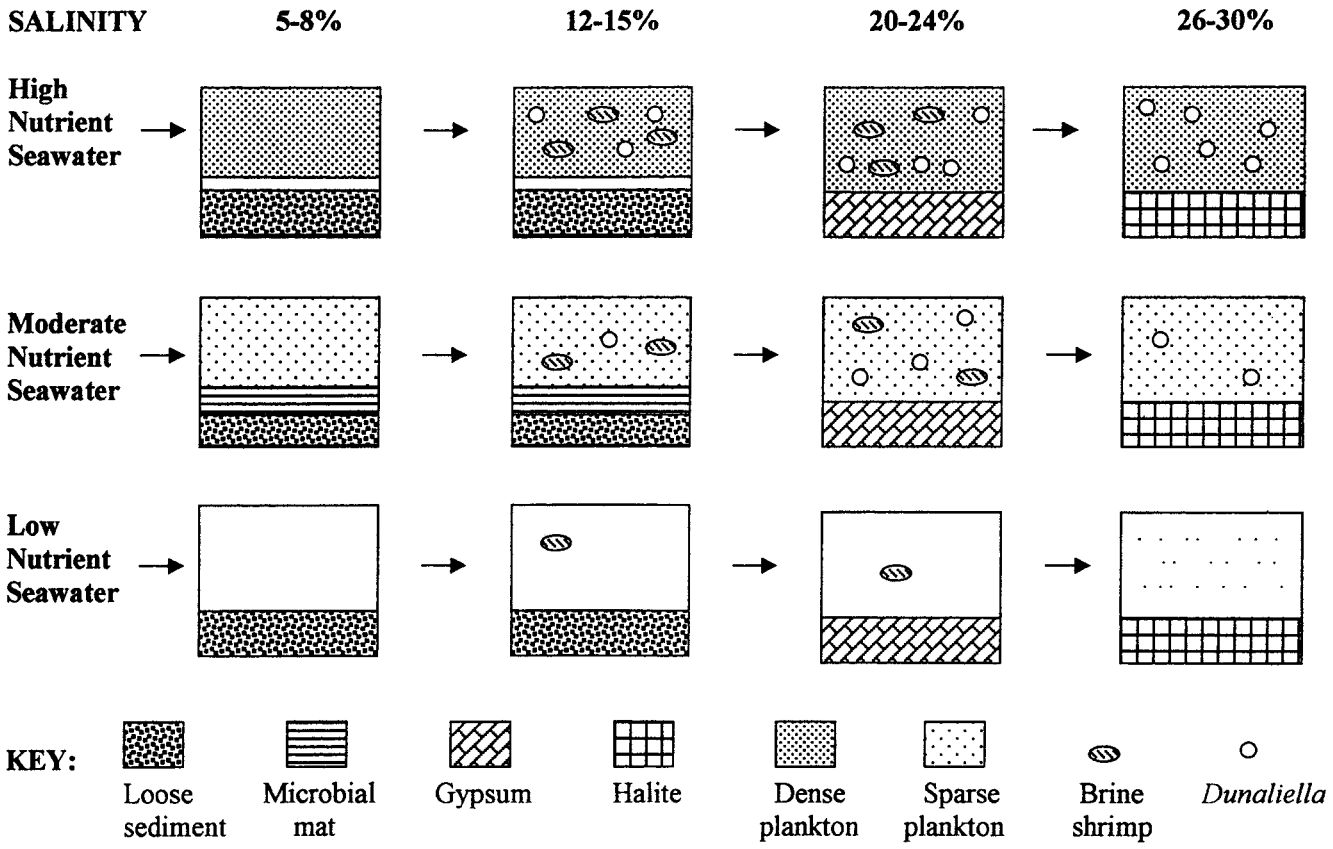

Figure 1 Development of planktonic and sediment communities in saltern ecosystems.

ponds (at salinities preceding gypsum precipitation) promote the dissolution of trace elements in the sediments. These cations would be chelated by dissolved organic acids in the brines and concentrated by evaporation downstream in the crystallizers. Such trace contaminants may co-precipitate with the NaCl or be trapped in fluid inclusions in the crystals. Rafted organic matter can also accumulate as wind-blown masses in ponds with a gypsum floor. In those areas, sulfate reduction activity is sometimes so high that the decrease in dissolved sulfate promotes the dissolution of gypsum (personal observation). Gypsum dissolution causes Ca^{2+} concentrations to increase in the brines. In the presence of high DOC (especially organic acids), Ca^{2+} tends to remain chelated and dissolved in seawater [4], and it could theoretically accumulate downstream with evaporation. These aspects of the biogeochemical model of NaCl production are hypothetical, as there are no published studies comparing the content of trace elements and Ca^{2+} in salt and associated brines produced in oligotrophic and eutrophic salterns.

Extracellular polysaccharides

At about 10% salinity in the concentrating ponds, certain bloom-forming cyanobacteria (*Aphanothece halophytica*, also called *Coccochloris elabens* by some researchers) secrete excessive polysaccharide mucilage during "unbalanced" growth. This condition is undesirable because the slimy masses float downstream to the crystallizer ponds and inhibit salt crystallization [1]. The environmental factors that trigger slime production in solar salterns are poorly known, but they have been investigated in other environments and cultures. Extracellular polysaccharide (EPS) production by algae and cyanobacteria typically occurs during stationary or declining culture, and is usually attributable to phosphate limitation (high N:P ratios) [6,7,25]. However, even diazotrophic cyanobacteria, such as *Anabaena* cultured in the absence of combined nitrogen, may accumulate substantial amounts of EPS [16]. In batch culture, EPS accumulated only during stationary phase growth when no nitrogenase activity could be detected. In chemostat culture, the greatest EPS concentrations (EPS:biomass ratio >1.5) were attained at low dilution rates.

In the light, photosynthesis continues to occur but the cells must expel excess carbohydrate in order to maintain the appropriate C:N:P balance. Lange [12] postulated that the formation of a thick, mucilaginous slime around cyanobacterial cells provides a micro-environment where essential nutrients are concentrated and become readily available to the cells. The voluminous sheath is not attacked by bacteria when other more assimilable organic matter is available. These slimes may scavenge phosphate and other nutrients, including essential trace metals. The EPS produced by the marine cyanobacterium *Cyanothece* removed >90% of the nickel, copper and cobalt ions from solutions due to anionic groups in the EPS which bind to cations [22]. We suggest that the thick mucilage of *A. halophytica* may also create an anoxic zone around the cells and an appropriate environment for nitrogen fixation by *A. halophytica* or associated bacteria, although this theory has not been tested.

While cyanobacterial slimes are a bane to solar salt production, they may be of considerable interest for novel industrial applications. Alternative uses include soil conditioners, wastewater

management and detoxification of metal-contaminated media [16]. Although the physiological and chemical attributes of *A. halophytica* and its slimes have not been described in the literature, applied studies of EPS have been conducted for the halophilic cyanobacterium *Aphanocapsa halophytia*. The EPS contained 10% proteins and 12% sulfated residues [26]. EPS production was optimized in a solid support culture system to achieve a production rate of 116 mg EPS/mg dry cells/day [15]. It is possible that future interest in saltern cyanobacteria may be directed away from salt production and towards novel industrial applications such as EPS production.

Brine management

Microbiological problems in the salterns (e.g., rafting, poor mat development and slime production) may be predictable based on a regular monitoring program of nutrient analyses, plankton and mat evaluations, climatic predictions and past history of the ponds. When "crises" occur, saltern managers try a variety of methods to mitigate the problems. Rafted material (which often accumulates on one side of the ponds due to winds) is sometimes physically removed from the ponds. Aeration systems that are used in sewage ponds are generally not employed, presumably due to the costs of installing such systems in large, shallow ponds. Some salterns have tried fertilization with commercial fertilizers [5] or septic tank wastes (proprietary communication to the author) in oligotrophic pond systems to encourage microbial development. When *Aphanothece* slimes are a problem, some saltern managers add sodium hypochlorite as a remedial method. The hypochlorite inhibits microbial activity or causes breakdown of the polysaccharides. The increase in Na^+ ions promotes crystallization of NaCl.

The chemostat-like process of microbial development in solar salterns is often disrupted by seasonal events or by management decisions. In locations with seasonally high rainfall, salinities in individual ponds may decrease or the managers may drain the ponds to protect the levees. When salinity decreases, managers often increase the residence time of brines in individual ponds to allow further evaporation. The decrease in salinity may cause lysis of sensitive organisms. Longer residence times may mimic the effects of lower dilution rates in continuous culture or they may trigger the appearance of attributes of stationary phase in batch cultures. Drainage of the ponds sets the stage for decomposition on the pond floors and a spike in fertilization once brines enter the system again and the microbial communities begin to develop. Seasonal flooding in a salt crystallizer was found to be associated with the appearance of halobacterial phages, suggesting that natural dilution events and lysis of microbial populations probably play a role in genetic diversity in hypersaline environments [27].

Some practical methods of analyses

There are no standardized GMP or quality control methods in the solar salt industry with regard to microbiological and nutrient analyses. The following summary of methods has been derived from about 20 years of experience in various solar salterns. Most analytical techniques are adapted from *Standard Methods of Seawater Analyses* [24], or similar standard protocols used in microbiological laboratories. In most cases, methods must be modified to avoid salt interference.

Whole brine analysis: salinity and turbidity

Gravimetric methods are not practical for measuring total dissolved solids as salts are hygroscopic and drying at elevated temperatures may release bound water from some mineral phases such as gypsum. The following temperature-sensitive instruments are commonly used to measure salinities or densities of natural brines: specific gravity or Baumé hydrometers, salometers or refractometers. In all cases, the temperature must be measured and appropriate calculations made to normalize the readings. In the field, Secchi disks may be useful to measure turbidity in ponds where the bottom is not visible. In the laboratory, turbidity readings may be measured in a standard turbidometer or spectrophotometer set to measure light scatter. We have adopted a spectrophotometric reading at 400 nm to measure "raw" (unfiltered) minus filtered or centrifuged brines (net turbidity) against a distilled water blank. In the crystallizers, turbidity is usually due to a combination of planktonic cells and microscopic NaCl crystals. Turbidity should be measured as soon as possible after brine collection and at field temperatures, as NaCl continues to precipitate, especially if the samples are chilled.

Separation of particles from brines

As brine density increases with evaporation, the brines become more viscous and increasingly more difficult to filter. Standard 0.2- and 0.45-μm filters work at seawater salinity, but they are impossible to use at elevated salinities. We have used GF/C filters as a compromise, although it is sometimes apparent from the color of the filtrate that some bacteria pass through the filters. In oligotrophic crystallizer brines, up to about 200 ml can be filtered through a 4.25-cm GF/C filter before salt particles clog the filter. In eutrophic crystallizers, sometimes only 20–30 ml can be filtered. An alternative method is centrifugation. Phytoplankton and sediment particles in seawater form a pellet at about $2000\times g$. In brines of greater than about 10% salinity, higher rates of centrifugation are needed. We routinely use $10{,}000\times g$ in floor model centrifuges or $13{,}000\times g$ in microfuges. In very eutrophic ponds with high planktonic densities, the concentration of cells collected in microfuge tubes (e.g., 6 ml concentrated as 4×1.5 ml) is often more than sufficient for chlorophyll *a* and protein analyses. However, when *D. salina* is abundant, centrifugation is problematic. *D. salina* may accumulate large amounts of β-carotene, a lipid that causes cells to float in centrifuge tubes.

Nutrient analyses

The selection of nutrient and biological parameters to measure depends on which factors are believed to be critical to operations or downstream predictions, cost and ease of measurement, especially for salterns in remote localities. Colorimetric analyses of standards prepared in hypersaline solutions usually show salt interference that prevents significant color development. We have found that the simplest method is to dilute the samples to the maximum salinity at which no salt interference can be detected. The following modifications were determined empirically by the author.

Dissolved reactive phosphate may be measured by the method of Strickland and Parsons [24]. Crystallizer brines should be diluted two-fold to avoid salt interference. We have found that

nitrate concentrations are typically low or non-detectable in saltern systems [8,9]. Crystallizer brines must be diluted two-fold to avoid salt interference for nitrate and nitrite analyses. We routinely measure the ammonia concentrations, which can vary widely in a pond system, across salinities and during the course of a year due to the activities of brine shrimp, phytoplankton and decomposition. Standard methods of ammonia analyses [23,24] are adapted to avoid salt interference by diluting the brines to $\leq$12.5% salinity. Water for dilutions and reagents must be freshly distilled or boiled immediately before use. One problem in some saltern facilities is that the QC laboratory for salt crystal analyses is often used for biological analyses. Salts are measured for their Mg^{2+} content by a titration method that uses NH_4OH. The odor of ammonia often permeates the room and contaminates any liquid open to the air.

Dissolved organic carbon

Dissolved organic carbon generally increases with brine concentration, indicating that passive concentration by evaporation is the likely mechanism [10]. It is not practical to measure total DOC by standard combustion methods for several reasons. Before injection, samples must be acidified and sparged to remove all carbonate, bicarbonate and CO_2. The total alkalinity of seawater-derived brines apparently increases with brine concentration while the CO_2 inflection point decreases [10]. It therefore takes more acid and longer times to sparge the brines. Brines with significant amounts of DOC tend to foam during sparging, and adequate precautions must be made to keep the foaming, acidic brines within the sparging chamber. Salt "bakes" onto the heated elements of some carbon analyzers, and only a few samples can be analyzed before the encrusting salt is impossible to remove.

It is therefore more practical to analyze indicator organic constituents by colorimetric methods for which salt interference is less problematic. We routinely measure dissolved carbohydrates, which are especially relevant when slime production occurs. The phenol–hydrazine sulfate method of Strickland and Parsons [24] is readily adaptable for salt interference. Gypsum-saturated brines should be diluted at least two-fold, and crystallizer brines must be diluted at least two- or four-fold. The reaction is highly exothermic and if the brine samples are not adequately diluted and vigorously mixed, the reaction may sputter explosively upon addition of the hydrazine sulfate reagent.

Suspended particles

The suspended particles (plankton, organic detritus such as fecal pellets, and inorganic sediments) are separated from brines by filtration or centrifugation as described above. Inorganic sediments enter through inlet pumps, as windborne dust or as resuspended bottom sediments due to wind activity in shallow ponds. Saltern managers can often control suspended sediments through modifications in pond designs. The planktonic biomass and the particulate organic loads are largely controlled by the nutrient levels. Regular observations by microscopy should be conducted, as sediment loads and biotas change with the seasons and with management practices that alter brine residence time and salinities in individual ponds. We have assessed sediment loads semi-objectively by microscopy and by comparing turbidity readings with measurements of chlorophyll *a* and proteins. We routinely measure chlorophyll *a* as an indicator of phytoplankton biomass, and total particulate protein as an indicator of total suspended organic matter using standard protocols [13,14,24]. Salt carried on the filter or in the pellet may precipitate in tubes used for chlorophyll *a* extractions, but it is easily separated by centrifugation or filtration before measurement in a spectrophotometer. Particulate protein analyses involve a NaOH solubilization step. During color development, salt on the filter or in the pellet apparently causes a slight floc to precipitate in the reaction tube. This floc can be removed easily by centrifugation or filtration just before measurement in a spectrophotometer. In remote saltern facilities where a bovine serum albumin (BSA) standard is not available for the protein analyses, we use a yeast extract standard. The yeast extract is calibrated against BSA in the home laboratory.

Oxygen and BOD analyses

Standard BOD bottles and Winkler titration reagents [24] are suitable for measuring O_2 in brines. At elevated brine concentrations, more sulfuric acid must be added to clarify the floc in the reaction. Both photosynthesis and respiration can be measured by this method. Photosynthesis by the $^{14}CO_2$ uptake method is not recommended because the apparent dissociation constants of the carbonate system (required for the calculations) are not known for concentrated brines of seawater origin.

Sediment analyses

When sites are chosen for construction of solar salt ponds, essentially no consideration is given to sediment composition and the associated biological and geochemical factors that may influence the salt production system. The primary considerations are accessibility to saline feedstocks, climate, inexpensive and flat terrain, and cost-effective transportation of the salt products. The broad range of oligotrophic to eutrophic conditions found among the world's salterns (Table 1) and their resulting effects on NaCl production are directly related to both nutrient inputs from the brine sources and nutrient inputs and recycling from the pond sediments. Sediment analyses are conducted in upstream ponds that precede the formation of gypsum crusts. In general, standard methods of sediment analyses can be employed. We usually take cores and analyze at least two different horizons such as 0–1 cm and 4–5 cm depths. Dry weights are determined after drying samples at 105–110°C. Sediment organic carbon is estimated gravimetrically after combusting dried, weighed samples at 500°C for 1 h. If there is any gypsum ($CaSO_4 \cdot 2H_2O$) in the sample, some weight loss will be attributable to mineral water loss. Sediment carbonate content can be estimated gravimetrically after acid hydrolysis (e.g., in 1 N HCl) or by combustion for 1 h at 1000°C to convert $CaCO_3$ to CaO. Gypsum is also acid-soluble.

Sediment phosphate is determined by overnight acid hydrolysis of dried, preweighed samples in a known volume of acid. We typically hydrolyze 200 mg of sediment in 10 ml 1 N HCl. After separating the sediment from the hydrolysate in a clinical centrifuge, aliquots of the hydrolysate are analyzed for reactive phosphate by standard techniques. Typically 0.1- or 0.2-ml aliquots of the hydrolysate are diluted to 2.0 ml for analysis. Higher concentrations of hydrolysates cause acid interference in the assay.

Other biologically related analyses

Some solar salt companies measure brine viscosity, which is a result of the effects of both concentrated ions and DOC. Wind,

temperatures and viscosity affect evaporation rates and the crystal habit of NaCl. Solid cubic crystals of salt that are free of brine inclusions are easier to wash and are more valuable on the market. When there is good brine mixing, solid crystals grow on the salt floors of the crystallizers. When brines do not mix and evaporation is high, floating salt crusts form on the brine surface. Surface crusts tend to be mushy and filled with brine inclusion, and they retard further evaporation. We predict that transparent exopolymer particles (TEPs) play a more pronounced role in the viscosity and chemical structure of solar saltern brines than they do in seawater [18,19]. TEPs are irregular-shaped, gel-like particles up to about 100 μm in length that form from EPS. In seawater, they are visible with staining and their abundance increases with increasing DOC. The role of TEP in saltern brines and especially in crystallization processes has not been explored.

Trace elements are not measured routinely in saltern brines or sediments. Given the potential role of microorganisms in mobilizing trace elements and concentrating them downstream, it may be prudent to monitor trace elements in salt, brines, slimes and source sediments, particularly in eutrophic systems. Salt interferes with the measurement of trace elements in brines unless precautions are taken [21].

Conclusions

Industrial microbiologists for solar salt production need a broad background in microbiology, and they must experiment with standard methods to make them work in strong brines. Microbiological and associated environmental analyses are essential when "crises" such as slime, rafting or odor problems occur. A future task for industrial microbiologists and engineers in this field is the creation of a more quantitative biogeochemical model of salt production. Although NaCl crystals are not directly microbial products, it is clear that upstream microbial processes can influence downstream crystal formation. By integrating the results of biological and chemical monitoring programs with physical parameters (temperature and evaporation rates) and objective evaluations of the salt product (crystal size and morphology), it should be possible to construct a more precise, predictive model for optimal solar salt production. Microbiologists may also lead the way to finding new industrial products from secondary metabolites of saltern microorganisms.

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