

Review

Graduation Towers and Pan Salt Production in Various Aspects—Case Study

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Abstract

Sodium chloride is a chemical compound that humans use in large quantities, both for consumption and for applications in many areas. This article aims to present various aspects of salt: production, health, tourism, cultural, environmental, and finally, historical. It mainly discusses the operation of the brine graduation towers—the last ones preserved in the technological line at the salt production plant. The authors aimed to illustrate the advantages and challenges associated with salt and to present solutions to the existing problems.

Keywords: graduation towers; saltworks; salt; sodium chloride; environment

1. Introduction

Throughout human civilization, salt emerged as a crucial commodity that frequently influenced the chances of survival. Salt has been used for a long time to keep meat fresh and to flavor meals and food items. Over the last 200 years, how salt is used has changed. The significance of salt as a basic material in various industries has changed how it is utilized. In the European Union, 51% of the salt produced is used in the chemical industry, in deicing 17%, in food 7%, in water treatment 6%, in feed 5%, and in other 14% [1].

In North America, the salt market share is deicing 43%, chemical 37%, food 4%, agriculture 3%, water treatment 1%, and other 12% [2]. It is difficult to obtain such data for Asia or Africa. Although only a small percentage of produced salt is consumed, there is no more important ingredient in the food industry than salt.

Salt has been extracted for centuries in various ways, depending on environmental conditions. In some places, nature itself exposed salt to the surface. Saltwater pools naturally form in depressions along ocean shores. Evaporating water causes the salt to crystallize naturally. Mimicking nature, humans still extract salt in this way, but on a larger scale. An example is the Trapani region in Italy (Figure 1).

“Sale Marino di Trapani (Italy)” designates Protected Geographical Indication (PGI) sea salt extracted in Trapani, Paceco, and Marsala. Production is traditional. Salt is obtained directly from the coastline, where the entire production area is located. The low-lying terrain along the coast (sometimes even slightly below mean sea level), combined with the exceptionally impermeable nature of the soil, favors the area’s suitability for salt production. During production, salt water is concentrated in sun-evaporated salt pans, centrifuged,



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mechanically ground in stone mills or stainless-steel roller mills, dried in fluid bed ovens, and finally mechanically sieved for the selection of defined particle size ranges [3].



Figure 1. Salines in Trapani Province, Italy (A. Makowska).

Natural salt formations in the Earth's atmosphere have also survived to this day and are exploited in salt deserts, such as the Salar de Uyuni (Bolivia), the Great Salt Lake Desert in Iran (Dasht-e Kavir), and the Great Salt Lake Desert in Utah, USA.

Another method of obtaining salt is the exploitation of underground resources: brine and solid salt deposits. Brine can naturally (under the influence of pressure/geological phenomena) flow out of the ground as a salt spring [4,5] or be pumped out after drilling. Solid underground salt deposits in the form of rock (halite) can be extracted in two ways. One is by flushing the salt deposit (injecting water and pumping out the brine), and the other is by extracting the salt using mechanical devices (in mines).

The depletion of natural resources and environmental degradation are leading to increasing attention being paid to sustainable development. Sustainable salt production involves many elements. Salt extraction methods with a low environmental impact are recommended, along with the use of sun and wind instead of fossil fuels, and minimizing interference with ecosystems. Responsible water and energy management and the reduction of CO₂ emissions are also emphasized. Using production methods that minimize the generation of difficult to manage byproducts is crucial [6]. Attention is paid to managing salt pans to minimize disturbance to local habitats. Sustainable production also means supporting local communities, their employment, and development, as well as ensuring safe working conditions for mine and saltworks workers.

Salt extraction sites are numerous, most of them with long-standing traditions around the world.

This manuscript comprehensively explores the multifaceted roles of salt (sodium chloride) and brine graduation towers, covering dimensions including production technology, health, tourism, culture, environment, and history. It aims to bridge technical, environmental, social, and cultural perspectives to advance sustainable salt production and consumption.

The aim of this work was to conduct an interdisciplinary study related to salt for two main reasons. Firstly, to characterize the material salt heritage, and secondly, due to the danger of the disappearance of the knowledge and techniques associated with graduation towers and pan salt production. To this end, the following specific objectives have also been set:

1. to characterize the last saltwork with graduation towers and compile the knowledge and know-how associated with the salt activity,
2. apply a broad approach to the topic, present salt production in detail, and document it well,

3. to show the values of the safeguarding of salt heritage in various aspects of sustainable development,
4. to find out the problems connected with sustainable salt use.

2. Materials and Methods

This study employed a qualitative research approach based on two primary methods: a query and field research. Combining these methods allowed for both an in-depth analysis of existing knowledge and the collection of direct observations from relevant individuals.

2.1. Query

The search included scientific databases: Web of Science, Springer, Elsevier ScienceDirect, Wiley, Scopus, and Journal Citation Reports, as well as the Polish National Library and a “Google Scholar” web search. A search for information (articles, books, and book chapters) on saltworks with graduation towers was also carried out in the following libraries: the Library of the University of Life Sciences in Poznań and the Library of the Bydgoszcz University of Technology. In our research, both terms, “graduation towers” and “saltworks”, and their Polish equivalents, “teżnie” and “warzelnie soli”, were used. No time range was entered when searching for data. The Web of Science, Springer, The Polish National Library, and Scopus databases yielded 118, 2, 2, and 5 records, respectively. No records matching the search terms were found in the Journal Citation Reports, Elsevier ScienceDirect, and Wiley databases.

The materials were then verified in terms of information about salt production based on graduation towers. The articles selected during the search were listed in the bibliography.

Access was also obtained to unpublished reports and internal documents of the plant.

2.2. On-Site Study

The methodology of the on-site study involved data through observation, interviews (with people associated with the saltwork), and visits to the graduation towers area and saltworks in Ciechocinek (Poland). Field visits permitted us to understand the plant operations and to document the most important and distinctive technologies and equipment used in salt production.

These research methods allowed us to obtain a comprehensive and integrated picture of the plant and the environment in which it operates.

3. The Salt Production Line with the Graduation Towers vs. Solar and Evaporation Vacuum System and Rock Salt

One method of obtaining salt involves obtaining brine, initially concentrating it, further evaporating the water through heating (i.e., boiling), crystallizing, and drying the salt. Brine concentration can be performed in evaporation basins (in countries with a hot climate) or using graduation towers, evaporation devices, and/or membrane filtration. To the authors’ knowledge, the last operating plant in the world using a graduation tower system for brine concentration is the saltworks in Ciechocinek, Poland. The graduation tower (Figure 2) is a structure made of a wooden frame with blackthorn branches.

The salt production process begins with pumping out brine, which is then directed to the top of the graduation tower and flows down by gravity. Branches separate the brine into droplets. The towers are used to increase the salt concentration in brine by partially evaporating it. Branches increase the evaporation surface, causing the salt in the solution to condense. Blackthorn is used in graduation towers because of its thorns. They increase the surface area over which the brine can flow, thus increasing the surface area for water evaporation. Blackthorn used in graduation towers should be harvested in winter, dry (to

prevent germination and leaf development), and placed at an angle to facilitate brine flow from the branches. During brine thickening, compounds (salts) including calcium, iron, magnesium, and potassium precipitate on the blackthorn. This is a natural but undesirable process. The above-mentioned substances precipitate from the brine. Salts cause the sloe to “stone” and lose its properties (Figure 3).



Figure 2. Graduation tower (S. Chudy).

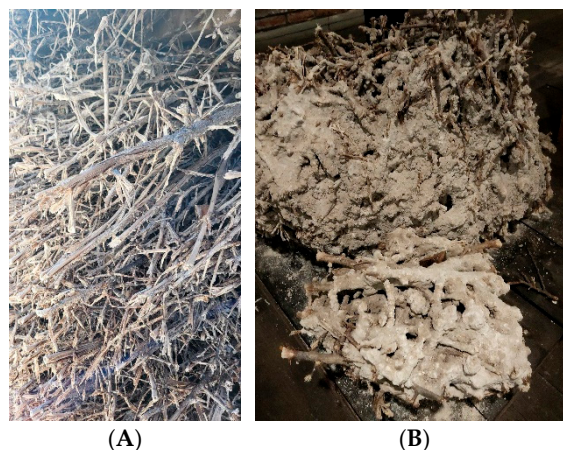


Figure 3. Blackthorn branches during (A) and after (B) exploitation (R. Kowalski).

The degradation rate of blackthorn branches is directly proportional to the operational intensity of the graduation tower.

The oldest remains of graduation towers in Poland date back to the 2nd–4th century AD. The saltern, which was a technological line with graduation towers, was recorded at the archaeological site in Inowrocław (near Ciechocinek, in Poland). Supposedly, they were a local innovation [7]. Graduation towers in Ciechocinek were constructed in the 19th century (1824–1856) and are the largest structure of their kind in Europe. It is a complex of three salt graduation towers (651.5 m, 723.8 m, and 366.2 m) with a total length of 1741.5 m and a height of 15.8 m each. The brine graduation towers in Ciechocinek were the last graduation towers in Poland built in accordance with the technological requirements of evaporated salt production [8].

Currently, brine for the graduation towers is extracted from a borehole drilled in 1911 (located in the center of Ciechocinek, under the “Mushroom” fountain) at a depth of 405 m. Its temperature, measured at outflow, is 13.3–14.8 °C, and salinity is 4.5%. The maximum operational capacity of the intake is 60 m³/ha, and current brine consumption is 36 m³/h. The graduation towers operate from April to October, when temperatures in Poland usually do not drop below 0 °C. The evaporation process then occurs with the expected efficiency.

The brine flows from the intake to the graduation towers through a pipeline approximately 473 m long and is then delivered to the top of the towers (Figure 4).

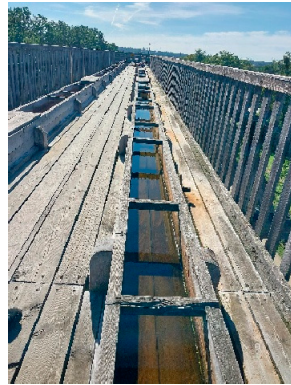


Figure 4. Top of the graduation tower (S. Chudy).

The graduation tower roof features two parallel troughs and four gutters (on the sides of the troughs) for brine drainage. The direction and speed of brine flow are regulated by wooden gates and valves (Figure 5).

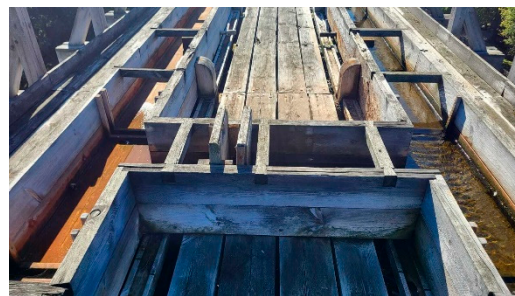


Figure 5. Gates and valves for regulating the side and power of the runoff (R. Kowalski).

The flow of brine down the blackthorn ridge is dependent on wind direction and always occurs on one side—the windward side. Brine flow requires constant monitoring of the wind direction. Brine flow is regulated manually. In the first graduation tower, the brine is concentrated to approximately 10% salt content, in the second to approximately 18%, and in the last to approximately 23%. Here, 36 g of sodium chloride dissolves in 100 g of water at room temperature. This means that a saturated salt solution is a 26.5% solution.

At the bottom of each graduation tower are original 200-year-old wooden tanks for the concentrated brine. Their total capacity is 10,480 m³. The rate of concentration in the graduation towers depends on wind force, air temperature, and air humidity. Although water evaporation begins at humidity levels below 100%, humidity levels below 70% are needed to effectively increase the concentration of the NaCl solution [9].

The largest volume of brine is stored in tanks beneath the graduation towers. Some of the concentrated brine is sold, while the rest feeds the nature reserve adjacent to the graduation towers, which is home to halophytic vegetation. Some of the brine is transferred via a 1.5 km pipeline to the saltworks. Two brine reservoirs are located there: a large one with a capacity of 700 m³ and a small one with a capacity of 166 m³.

Saltwater deposits are exploited sustainably. In 2024, 53,306 m³ of salt water was transferred to the graduation towers—8000 m³ of preconcentrated brine was obtained, of which 264 m³ was used for salt production. In 2025, 44,665 m³ of salt water was pumped, of which 586 m³ (88 m³ concentrated brine) was used for salt production. Salt production is periodic.

The plant was launched on 21 October 1832 (its trial run took place in 1830) and continues to operate almost unchanged [8]. The heat for heating the brine comes from a coal furnace located directly under the brine tank (Figure 6).



Figure 6. Coal furnace for heating the brine (S. Chudy).

Because the factory is also a historic monument, the coal furnace cannot be replaced with any other energy source. The brine is preheated in a preheater to approximately 40 °C and then transferred to the boiling tank. The temperature of the concentrated brine reaches approximately 105 °C, the water evaporates, and the salt crystallizes and falls to the bottom of the tank. The salt is then removed and placed on boards placed above the tank, where it is dried (Figure 7). The dried salt is stored in bulk. Before packaging, the salt is additionally dried in a drum dryer (Figure 8).



Figure 7. Drying the salt on the boards above the bathtub (S. Chudy).



Figure 8. Drum dryer (R. Kowalski).

According to WHO Standards [10] and the National Agency for Food and Drug Administration and Control [11], the content of NaCl in salt shall not be less than 97%. The salt production process is shown in Figure 9.

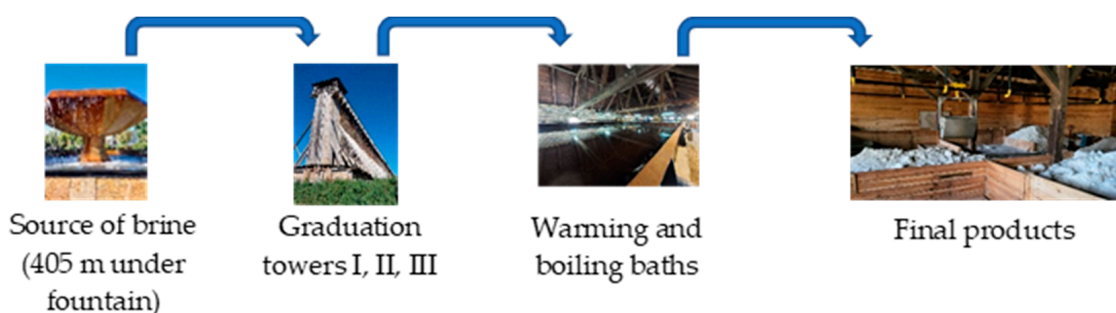


Figure 9. Diagram of the salt production line (S. Chudy and R. Kowalski).

A global trend is the use of various additives in salt. Germany and Switzerland fluoridate salt to improve oral health. Folic acid, which is very important for women of childbearing age to prevent fetal defects during pregnancy [12], can also be found in salt from some manufacturers [13]. Iodine is a mandatory additive to table salt in many countries—added in the form of potassium iodide or iodate. Salt from Ciechocinek is enriched with potassium iodide.

During salt production, three additional products are created. They are sludge, omok, and lye (bittern; Figure 10). Sludge is the lower layer formed during salt production in the evaporation tank. It is a mixture of sodium, calcium, magnesium, and iron salts. Omok is a scale that forms at the bottom of the salt pan during salt evaporation. It is used as salt for animals and road salt.



Figure 10. Products obtained in the brewhouse. Top: salt and sludge; bottom: fine fraction of omok and lye.

Lye is the liquid solution remaining after salt production. In addition to sodium chloride, it contains calcium, magnesium, and iron salts. Sodium, calcium, magnesium, and iron are present as cations. Chlorine, iodine, and bromine are anions. Sludge is packaged, and the bittern is bottled and sold as an additive to home baths.

During production of salt using vacuum condensation, the following co-products are formed: calcium carbonate (CaCO_3), calcium sulfate (CaSO_4 , gypsum), and magnesium sulfate (MgSO_4)—removed from the brine to prevent contamination of the final salt product. After crystallization of NaCl from brine, magnesium chloride (MgCl_2) and potassium chloride (KCl) can be isolated. A highly concentrated solution of magnesium, potassium, and sulfate salts left after separating the NaCl crystals is called bittern (mother liquor, potassium–magnesium lye).

Calcium sulfate (gypsum) and calcium carbonate precipitate in the early stages of evaporation in the solar system. Magnesium sulfate appears in the later stages of brine thickening. Magnesium chloride (MgCl_2) remains in the final solution, often recovered or discharged. Potassium chloride (KCl) is a component of late bittern; in some plants, it can be recovered, for example, for fertilizer production. The last co-product is bittern [14,15].

Good-quality rock salt does not require purification processes.

Both graduation towers and salt pools (in solar system salt production) are used to produce salt through evaporation of water from a saline solution. Multi-pond solar salterns consist of a series of interconnected ponds with increasing salinity, reaching the sodium chloride saturation level [16,17]. In countries with hot climates, this process typically takes place in outdoor salt pools. To ensure year-round production, improve the quantity and quality of salt, and speed up production, geoisolators (for the bottom of pools) and closed systems in prism form can be used. Solar energy, acquired from solar panels, is also used to maximize its potential in salt production plants [18]. In artisanal sea salt production, the Sun is used for the salt concentration in brine and natural salt crystallization. It is the most environmentally friendly salt production method.

Modern industrial plants involve the use of vacuum evaporators for preconcentration of brine. Next, the salt crystallization is carried out in tanks or crystallizers, followed by optional centrifugation and final drying. An alternative method to the salt crystallization step from brine was proposed by Pambudi et al. [19]. This method involves spray-drying the concentrated brine. The salt thus obtained is characterized by a whiter color and is “smoother” than that obtained using conventional methods. The bright white is the result of using prism housing, which helps minimize dirt. The white color is also associated with filtration conducted to separate other minerals. In the USA, vacuum and solar salt account for 85% of all production. Salt extracted from mines accounts for 13%, and salt in brine for 2% [20].

Salt production essentially relies on one of two processes: the evaporation of saline water or extraction by mining. Depending on the origin of the salt water or the specific location or device where the condensation or crystallization of the salt takes place, the classification includes sea salt/artisanal sea salt, rock salt, pan salt (evaporated vacuum salt or using graduation towers), and salt lake salt.

The European Commission report [21] contains estimated data comparing the environmental impact of the production of three types of salt. Production of sea salt (solar salt concentration and crystallization), rock salt, and evaporated vacuum salt consumes energy at 10, 26, and 223 (kWh/t salt), respectively. CO₂ emission (kg/t salt) and water consumption (liter/t salt) in the production of sea salt are 3 and 10–100, in the production of rock salt 12 and 0–20, and in the production of evaporated vacuum salt 93 and 100–750, respectively. It is imperative to acknowledge that the source data presented here are not definitive or exhaustive. They encompass total energy and water consumption per ton of salt, but do not provide calculations. No conversion factor is provided for carbon dioxide emissions (it allows for the calculation of carbon dioxide emissions resulting from electricity consumption).

The following two main sources of CO₂ emissions can be distinguished in the discussed saltworks, in Ciechocinek:

1. Combustion of coal to generate heat (for brine evaporation and salt crystallization). Producing 1 ton of salt requires 6 tons of hard coal. Direct CO₂ emissions during the combustion of hard coal are 2.73 kg CO₂/kg hard coal [22].

Hence, 6 t of coal $\times$ 2.73 tons of CO₂ = 16.38 tons of CO₂/ton of salt.

2. Indirect emissions from electricity include electricity used for transporting brine (pumping) and drying salt before packaging. In Poland, 70% of energy comes from fossil fuels. Electricity consumption translates into CO₂ emissions. To calculate CO₂ emissions (kg) from electricity, multiply the consumption in kWh by the average emission factor, which is approximately 0.597 kg CO₂/kWh (for the Polish energy sector) [23].

Pumping brine to produce 1 ton of salt consumes 157 kWh.

Drying a ton of salt in a drum dryer consumes 2880 kWh. The sum of the energy used is 3037 kWh.

Multiplying the energy by the conversion factor gives:

$$3037 \text{ kWh/t of salt} \times 0.597 = 1813 \text{ kg of CO}_2 \text{ (1.813 t)}.$$

The sum of emissions of CO₂ is 18.193 tons per one ton of produced salt. There are many options for replacing the old coal furnace with ecological heat sources, but under current legislation and the plant's status as a historical monument, such changes are prohibited. As stated by Hueso-Kortekaas and Iranzo-García [24], changes to heritage sites carry controversy among conservationists because they see it as a threat to the values they defend. It is worth emphasizing that salt production in Ciechocinek does not consume water (as is the case when salt deposits are washed with freshwater to obtain brine), there are no underground empty chambers (as is the case with rock salt), and no expensive specialized machinery is used. Despite this, salt production using the technology described is not a profitable venture. The salt production line requires extensive maintenance: replacing the sloe (approximately every 10 years), structural repairs to the graduation tower, and repairs to the saltworks. The graduation tower has a volume of 200,000 m³, including 90,000 m³ of sloe. Between 2019 and 2023, nearly 22.5 million PLN (USD 6.25 million) was spent on these purposes. Due to the problems described, salt production is based on a compromise (Table 1). Moreover, the development of education and salt tourism is in conflict with the desire to preserve the character of the place as a quiet, peaceful resort.

Table 1. Reasons for the necessity of compromise in salt production.

Characteristics of Production Conditions	Versus Fact
High process costs	Heritage, desire for museum development, tourism, and education
CO ₂ production	Historical monument and the inability to implement ecological and energy-saving changes
Natural conditions limiting the operation time of graduation towers due to frost	Population growth of an average of 0.85% per year induces an increase in food production (including salt)
Large surface area of the entire production line	Trend of increasing production efficiency due to decreasing production areas

Unfortunately, social, economic, and historical changes in recent decades have led to the disappearance of numerous salt production sites around the world. This loss is estimated at 90%. For example, in Greece, in 2008, only eight saltworks were active (dormancy rate of 71.4%). Due to this overall saltscape loss, many countries are taking steps to transform saltworks into “cultural geoheritage”.

In the process of patrimonialization (transformation from production activity to multifunctional economic activity based on heritage), four stages are usually distinguished:

- cessation or irreversible decline of production,
- activation (usually by non-governmental organizations or public administration),
- professionalization, in which the heritage asset/landscape is cared for by people or organizations with expertise in this topic,
- consolidation—a specific multifunctional entity is created (e.g., salt production, tourism, wellness, and education). At this stage, stability and a strategic long-term vision are ensured [24,25].

The Ciechocinek salt pans—a geoheritage site—have always been characterized by their multifunctional nature (salt production, mineral water production, tourism, and wellness). The most profitable part of the health resort, the hotel and spa part, and the production of mineral water support the maintenance of the saltworks. The functioning

graduation towers are the core of the spa. Patients who come for spa treatment benefit from physiotherapy treatments at the centers and walks around the seasonal graduation towers. It is worth noting that the brine does not flow through the graduation towers in a closed system. Hence their uniqueness, both in terms of technology and their impact on human health.

For several years, the salt pans have been expanding their reach to include educational activities. In 2017, the President of Poland signed a document recognizing “Ciechocinek—the graduation tower complex and saltworks, together with the graduation towers and spa parks” as a historical monument. In 2020, the Museum of Saltworks and Spa Treatment opened. Due to its heritage value, the site is protected to a certain extent. Heritage management is challenging, but the Ciechocinek salt pans are a good example of how to work with geoheritage.

4. Salt Production as an Important Factor in the Development of Many Other Sectors of the Economy

In parallel with the extraction of brine, the development of saltworks, and the construction of graduation towers, spa resorts developed across Europe. In Germany, these included Bad Dürrenberg, Bad Kreuznacher, and Bad Rothenfelde. In Poland, these included Ciechocinek, Inowrocław, Kołobrzeg, Busko, and Rabka. The oldest operating graduation tower in Europe, dating back to the 16th century, is likely located in the German town of Bad Kissingen. Salt production in this place was stopped in 1968.

The first brine drillings for saltworks in Ciechocinek took place around 1805 [26]. Simultaneously, its use for medicinal purposes began. Drinking brine and bathing in salty waters were recommended. According to materials collected by Marcinek and Myczkowski [27], patients were already coming to Ciechocinek for brine baths as early as 1827. In 1836, the first mini spa with four baths was opened in Ciechocinek. In 1842, the Ciechocinek Health Resort opened. By 1847, the new Spa House had 36 baths.

In health resorts, in baths and inhalations, therapeutic benefits of salt are used [28]. According to Petersen et al. [29], in some skin diseases, salt baths provide a significant reduction in pain (91%), skin odor (31%), and skin discharge (44%).

Nowadays, graduation towers function as a significant inhalation zone in wellness retreats. A complex brine distribution system in the graduation tower is essential to control its flow according to wind speed and direction. However, significant salt losses are unavoidable, as small droplets are always blown away. This drawback during salt production, however, is an advantage during inhalation. The tanks or cisterns collecting the concentrated brine beneath the graduation towers are covered with boards to protect the brine from dilution by rainwater. Today, this measure is only necessary in Ciechocinek, where the brine is still transferred to the saltworks. In other spa resorts, such protection is no longer used, as it is unnecessary.

The microclimate around the graduation towers is used in the prevention and treatment of upper respiratory tract diseases, emphysema, arterial hypertension, allergies, sinusitis, vegetative neurosis, and general exhaustion. The design of graduation towers resembles that of subterranean salt chambers, providing therapeutic benefits for those suffering from chronic pneumonia and asthma. Brine inhalations cleanse the respiratory tract, moisturize the mucous membranes, and soothe inflammation [30,31].

In Ciechocinek, the active compounds affecting the respiratory system are primarily sodium chloride, bromine, iodine, and iron compounds. A characteristic iodine odor is noticeable in the vicinity of active graduation towers. The amount of therapeutic aerosol and the direction and range of brine particle dispersion vary depending on its density and current meteorological conditions: sunlight, wind direction and speed, and precipitation.

The highest aerosol release near active graduation towers occurs on sunny days and with moderate wind speeds. Stronger winds cause excessive dilution of brine particles in the air [32].

The spraying of brine creates a microclimate around the graduation tower, which is one of the spa's primary therapeutic factors. Studies of graduation tower aerosol in Ciechocinek revealed the presence of salt crystals up to 300 m from the graduation tower [27].

Kalwasińska et al. [33] analyzed salted water received from the Ciechocinek source (405 m underground) after concentration of the solution. The salt content increased from 5.1% to 26.7% after three stages (successively on three graduation towers). The microbial cell density doubled during concentration from $2.24 \pm 1.05 \times 10^7$ cells/mL to $5.47 \pm 0.46 \times 10^7$ cells/mL, and the bacterial type changed. Identified bacterial species richness and diversity increased along the salinity gradient.

Graduation towers (except Ciechocinek) are no longer operated for industrial salt production purposes. At present, they function primarily as a part of SPA and wellness infrastructure and are often operated in a closed-loop circulation system. A two-year investigation by Bodziacki and Wolny-Koładka [34] into the brine of a city's closed-cycle graduation tower identified *E. coli* (16 CFU/100 mL brine), *E. faecalis* (34 CFU/100 mL), and *C. perfringens* (8 CFU/100 mL), which can lead to infections if ingested or inhaled. Similar issues are observed in city fountains [35,36]. Studies by Nag et al. [37] showed that a dose of 26 CFU of *E. coli* in aerosol per day, which is apparently low, indicates some risk. It is also worth noting that *E. coli* strains differ in infectious doses. However, the regulations do not specify the methodology or the range of permissible values of microbiological contamination in outdoor air, so consistent monitoring of brine and water quality is essential for these facilities to serve their intended purposes. Although UV radiation, ozonation, and microfiltration are potential purification methods for brine and water, current literature lacks data on the specific techniques and effectiveness of disinfecting brine in municipal graduation towers. Further research is necessary to pinpoint the most effective, economical, and recommended disinfection approach. From an epidemiological perspective, it is necessary to introduce legal regulations regarding the sanitary and hygiene conditions of closed-cycle graduation towers. Reports of poor microbiological conditions of brine in closed graduation towers have not yet influenced government regulations.

The state of preservation of the industrial and spa complex largely reflects its historical state. Ciechocinek has approximately 240 buildings of historical significance [27]. A railway line reached Ciechocinek in 1867. The line was unused between 2014 and 2025, but its reopening is planned after renovations are completed, at the end of 2025. The brewing and medicinal industries influenced Ciechocinek's architecture, the construction of parks, promenades, spa houses, and guesthouses. Near the graduation tower, there is a halophyte reserve supplied by the graduation tower waters. Among other plants growing there is *Solicornia*, a plant protected in Poland (Figure 11). The rarity of this plant indicates that salt exploitation in this area has not disturbed the natural environment.

The occurrence of this plant can also be considered a side effect of salt production. However, many places around the world are beginning to see halophyte cultivation as a development opportunity. This occurs in both naturally occurring saline areas and in places where increasing salinity and significant soil degradation will necessitate changes in agricultural production methods. These salt-tolerant plants represent a viable agricultural alternative for many regions. According to Ladeiro [38], halophyte cultivation can be considered in the context of food, forages, oilseeds, straw, etc.

Tłoczko et al. [39] studied the effect of 200 years of graduation tower operation on the properties of Ciechocinek soils. Salinized soils were found only in the area limited by the graduation towers and in the immediate belt surrounding them. According to the

Food and Agriculture Organization, this area is classified as moderately saline soils, of the second salinity class.



Figure 11. *Solicornia*.

Rock salt mining is also associated with the development of many branches of the economy. The permanent changes brought about by salt mining in the mineral (rock) form are underground excavations. In disused mines, the resulting underground chambers are being developed, among other things, into health resorts. Speleotherapy is based on the therapeutic properties of the underground environment and its microclimate. This therapy is used by health resorts established in inactive salt mines, including in the Czech Republic (Zlaté Hory), Romania (Turda), Germany (Berchtesgaden and Ennepetal), Austria (Bad Gastein), Slovakia (Banská Bystrica), Ukraine (Solotwino), and Poland (Wieliczka and Bochnia). Occasionally, disused salt mines are repurposed as underground tourist attractions (e.g., Wieliczka, Poland, and Hallstatt, Austria).

The lack of chemical reactions between salt and petroleum products allows the use of the post-mining space in the salt deposit as underground cavern storage of hydrocarbons. Presently, this method represents the most secure and efficient approach to fuel storage, ensuring that it does not endanger the natural ecosystem. The characteristics of salt enhance the suitability of underground storage facilities for hazardous materials, such as radioactive waste, by utilizing salt formations as containment chambers [40].

One way to use preserved underground salt chambers for contemporary purposes is as places of religious worship (churches, chapels, and altars). The main factors determining the possibility of functional adaptation in this direction are atmosphere in the mine, scenery of the mine underground, isolation from disturbing factors, and presence of old cult objects [41].

Given the threat of an escalating Russian–Ukrainian war, it seems reasonable to convert and utilize underground salt chambers as shelters or food storage facilities. Currently, only Switzerland in Europe provides all its citizens with shelter space.

A rock made of salt is called halite. Halite can also be used as a building material (salt houses in Bolivia). Pink halite, in particular, is used to make various kitchen boards: for chopping, serving snacks, and as a baking/grilling stone. Halite is also very effective and is often used by interior decorators (salt walls and lamps). This applies especially to colorful varieties. Throughout history and in modern contexts, artists have utilized salt as a material for sculpture. Salt sculptures are part of the heritage of salt mining. Initially, the sculptures were used to decorate underground chapels, which were created in the 17th century in the salt mines, e.g., in Wieliczka (Poland), and in the following centuries also in Bochnia (Poland). In the 20th century, Poland experienced a notable advancement in salt sculpture, particularly within the Kłodawa salt mine. Salt sculptures also decorate the underground cathedral in the Realmonte mine in Sicily. In regions beyond Europe, notable salt sculptures have been crafted in locations like the Zipaquira salt mine in Colombia and

the Khwera mine situated in Pakistan [42,43]. Salt sculptures are found mainly in religious sites in old mines.

SWOT analysis of salt heritage and saltscapes was done by Hueso-Kortekaas and Iranzo-García [24]. They noted that old salt mines around the world focus on four areas of activity and development: artisanal salt production, tourism, education, and health-promoting products and services. Threats to old salt plants include difficulties in securing financing, excessive tourism development, the trivialization of heritage (organization of mass events), and imitations of artisanal products by big corporations.

5. Striving for Sustainable Salt Consumption, Its Production, and Export

Minimum and maximum recommended daily salt intakes for adults are 1.3 g [44,45] and 5 g [46], respectively. The 2013 Harvard Public Health report [47] indicates that the highest salt consumption occurs in Asia, and the lowest in Africa. In Asia, the Chinese consume the most salt—17.7 g/day, in Europe—Hungarians—14.3 g/day, and in Africa—Zimbabweans—8.4 g/day [48]. So far, no country can demonstrate the WHO recommended intake of 5 g/person.

To reduce overall salt intake, very often it is recommended to limit consumption of processed and restaurant foods. To maintain balance, i.e., preserving jobs, developing ready-to-eat food, and catering services, reducing the amount of salt in food and in recipes seems to be a better solution.

Sustainable salt production addresses how to source and distribute salt in a way that minimizes environmental impact and supports local communities. Sustainability initiatives include reducing energy consumption, rational water management, protecting ecosystems, and supporting local communities.

Consumers can learn about the actions producers take from the product label, among other things. Sustainability logos can be found on salt labels. These inform consumers, for example, that renewable energy is used in production, that the product is eco-friendly, fair trade, that the packaging is recyclable, and so on.

Global salt production is not coordinated in any way. Most countries produce salt. However, China was the world leader in salt production in 2024, accounting for 20% of global production (by volume). The United States is second in the ranking (14% of global production). In Europe, Germany is the leader (6% of global production) [20]. In global salt exports (by value), according to data from 2024, China, Japan, and India lead [49].

An important aspect of sustainable development in salt production is the use of environmentally friendly packaging. A marginal number of salt plants package salt in cardboard or glass. Unfortunately, most salt, even with documented geographical origin and PGI (Protected Geographical Indication) or PGO (Protected Geographical Origin) labels, is packaged in plastic. Approximately 40% of global plastic production is used for packaging. In 2021, the EU recycled 38% of plastic packaging waste [50]. In line with sustainable consumption patterns, it is important to support actions aimed at reducing plastic consumption.

Currently, the market offers new-generation food packaging, including rPET (recycled PET with 30% recycled plastic), WPC (wood–plastic composite made from natural components and thermoplastic polymers), and biodegradable PLA—plastic obtained from renewable sources (e.g., corn starch and sugar cane).

6. Negative Impact of Salt on the Environment

An excessive amount of salt is extracted and utilized, which is problematic from a sustainability standpoint. Salt is used in places where it gets really cold to remove snow and ice from roads [51]. In the United States, around 70% of people live in areas that deal

with snow and ice [52]. The amount of deicing salts used has tripled over the last 45 years. In the USA, deicing on highways makes up about 41% of all salt used, while only about 4% is used in food processing [20]. While the use of deicing salts is necessary, it has a negative impact on the environment. These negative impacts include effects on plants and trees near highways and streets, contamination of water sources, air contamination by powdered salts, and corrosion of reinforced concrete, cars, and trucks. Road salts adversely affect the condition of buildings, stairs, and sculptures that come into contact with them [53,54].

Road salt flows with melted ice into water networks (rivers and lakes) and penetrates groundwater. This leads to the salinization of freshwater, which threatens aquatic organisms, degrades water quality, and causes premature plumbing failures [55]. Salt alters the physicochemical properties of soil and disrupts its structure (affecting its particles). It leads to reduced permeability of soil, destruction of beneficial microorganisms, and damage to plant root systems, causing them to wither. Increased sodium concentration in the soil reduces water availability for plants and lowers its fertility. Salt can be toxic to wild and domestic animals, both through direct contact (e.g., with paws) and through ingestion of salted water or food. High concentrations of salt are particularly dangerous to birds and amphibians. As Szklarek et al. [56] emphasize, the significant impact of salt on the environment cannot be ignored.

Research results indicated that calcium chloride is more effective at melting ice than rock salt. Magnesium and calcium chloride salts require 1/3 the amount of road salt to melt the same amount of snow and ice. Completely replacing road salt with alternative deicers (e.g., calcium chloride or calcium magnesium acetate) is not a realistic option today given budgetary constraints. There is no perfect replacement for road salt; therefore, the issue remains a scientific challenge for researchers (including chemists and environmental engineers). Environmentally friendly alternatives are used locally [57]. Common household items, such as sand or coffee grounds, may be sufficient tools to prevent skidding on ice around one's household [58]. All ecological solutions proposed so far (including the use of cheese brine and beetroot juice) remain merely proposals. Laboratory research has not been translated into industrial practice.

Not only human activity, which involves the increasing use of salt (in roads, agriculture, and the chemical industry), but also changing climatic conditions (global warming and frequent droughts), will contribute to land salinization. The areas most susceptible to desertification and soil salinization are arid regions. Salinization is the accumulation of water-soluble salts in the soil substrate. In the initial stage, salinity affects the metabolism of soil organisms and reduces soil productivity. In the advanced stage, it destroys all vegetation and other soil organisms. As a consequence, fertile and productive lands turn into arid areas and deserts. Water and soil salinity will likely increase. This will result in an increase in the demand for irrigation [59].

An example of the negative changes (related to salt) that humans can cause in their environment is the Monte Kali landfill in Germany. This landfill consists primarily of sodium chloride. A potassium mining plant has been operating there since 1976. A byproduct of this production is sodium chloride, produced in such quantities that the mountain on which the waste is deposited is now over 500 m above sea level. It has become both a local attraction and a problem. In coastal countries with water shortages, freshwater is obtained through desalination. The concentrated brine is discharged into the sea as waste. The negative impact of salinity on the environment (water resources and soil) was demonstrated in studies by Feld et al. [60] and Hagage et al. [61].

As suggested by Alberti et al. [62], brine in the Persian Gulf countries, for example, should be used in table salt production plants or, for example, in sodium chloride

production plants used in petroleum refining. Such actions are aimed at protecting the environment and producing salt at a competitive price.

7. Conclusions

Based on the presented material, the following conclusions can be drawn:

1. To preserve material heritage, efforts should be made to manage aging saltworks. Salines may change, but they do not have to disappear.
2. To increase the profitability of saltworks operations and reduce CO₂ emissions, a change in legislation is needed. With both industrial heritage and the environment in mind, opportunities for changes in the operation of historical monuments should be introduced (in this case, changes to the saltworks' brine heating system), and each case should be considered individually.
3. Understanding conflict issues and necessary compromises is crucial to the success of sustainable development efforts worldwide. Adapting educational messages and legal procedures to local circumstances is crucial.
4. Disused salt mines are being converted into museums, sanatoriums, radioactive waste storage sites, etc. There is a need to verify whether they can be adapted for use as shelters and/or food storage facilities.
5. There is a need to promote the use of eco-friendly packaging in the food industry, including the salt industry.
6. Due to the increasing salinity of land and water, there is a growing need to find a replacement for sodium chloride used in road construction.

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