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Corrosive phenomena in photovoltaic and agrivoltaic structures

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Abstract

The rapid expansion of agrivoltaics (AGV) introduces unprecedented durability challenges for metallic support structures. Unlike traditional solar plants, AGV foundations face a chemically aggressive biochemical reactor. This thesis investigates corrosive phenomena on galvanized steel, Zn-Al-Mg alloys, and Corten, driven by irrigation, tilling, and agrochemicals.

To quantify these stresses, the research contrasts the bivariate ISO 12501-2 standard with the comprehensive DIN 50929-3 framework. A standardized field inspection protocol was developed for the highly vulnerable air-soil transition zone. This involves localized excavation, ultrasonic residual thickness measurements, and in-situ evaluation of critical soil parameters using portable probes.

Applying this methodology across nine European installations revealed stark contrasts in structural health based on localized soil chemistry. Plants in highly conductive or severe environments (e.g., Pavia, Almeria) exhibited catastrophic coating failures rapidly. Conversely, structures in highly alkaline, resistive soils (e.g., Rovigo) remained practically pristine.

Empirical data confirms a profound correlation between soil parameters and accelerated corrosion, validating the DIN 50929-3 standard for AGV contexts. Comparative analysis with failed vineyard posts proved that fertilizer accumulation plummets soil resistivity, triggering severe pitting. This lays the groundwork for a new predictive model replacing historical uniform corrosion baselines.

Ultimately, the AGV environment is unequivocally more aggressive than standard PV contexts, with the air-soil transition zone being the primary failure point. To ensure a 30-year design life, the study proposes passive (sleeves, polyurethane coatings, concrete collars) and active protections (heavy galvanization, Zn-Al-Mg alloys, split-pile designs). Finally, the research advocates for predictive maintenance by integrating continuous geochemical monitoring into existing agronomic sensor networks to proactively prevent structural failures.

Key-words: agrivoltaics ; soil corrosivity ; galvanic corrosion ; transition zone ; weathering steel ; fertilizers.

Abstract in italiano

La rapida espansione dell'agrivoltaico (AGV) introduce sfide senza precedenti per la durabilità delle strutture di supporto metalliche. A differenza dei tradizionali impianti solari, le fondazioni AGV affrontano un reattore biochimico chimicamente aggressivo. Questa tesi indaga i fenomeni corrosivi su acciaio zincato, leghe Zn-Al-Mg e Corten, guidati da irrigazione, lavorazioni del terreno e impiego di prodotti agrochimici.

Per quantificare questi stress ambientali, la ricerca confronta lo standard bivariato ISO 12501-2 con il quadro analitico completo della norma DIN 50929-3. È stato sviluppato un protocollo standardizzato di ispezione sul campo per la zona di transizione aria-suolo, altamente vulnerabile. Questo prevede scavi localizzati, misurazioni a ultrasuoni dello spessore residuo e la valutazione in situ dei parametri critici del suolo tramite sonde portatili.

L'applicazione di questa metodologia in nove installazioni europee ha rivelato netti contrasti nello stato di salute strutturale in base alla chimica localizzata del suolo. Gli impianti in ambienti altamente conduttivi o severi (es. Pavia, Almeria) hanno mostrato rapidamente cedimenti catastrofici del rivestimento. Al contrario, le strutture in terreni altamente alcalini e resistivi (es. Rovigo) sono rimaste praticamente intatte.

I dati empirici confermano una profonda correlazione tra i parametri del suolo e la corrosione accelerata, validando lo standard DIN 50929-3 per i contesti AGV. L'analisi comparativa con pali da vigneto deteriorati ha dimostrato che l'accumulo di fertilizzanti fa crollare la resistività del suolo, innescando un grave pitting (vaiolatura). Ciò pone le basi per un nuovo modello predittivo che sostituisce i riferimenti storici basati sulla corrosione uniforme.

In definitiva, l'ambiente AGV è inequivocabilmente più aggressivo rispetto ai contesti FV standard, e la zona di transizione aria-suolo rappresenta il principale punto di cedimento. Per garantire una vita utile di 30 anni, lo studio propone protezioni passive (guaine, rivestimenti poliuretanici, collari in calcestruzzo) e attive (zincatura pesante, leghe Zn-Al-Mg, design split-pile). Infine, la ricerca promuove l'adozione della manutenzione predittiva, integrando il monitoraggio geochimico continuo nelle reti di sensori agronomici esistenti per prevenire in modo proattivo i cedimenti strutturali.

Parole chiave: agrivoltaico ; corrosività del suolo ; corrosione galvanica ; zona di transizione ; acciaio weathering ; fertilizzanti.

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1 Chapter 1: the agrivoltaic context and environmental stress factor

1.1. Energy evolution from ground-mounted PV to agrivoltaics (AGV)

The current European and Italian energy context is driven by the urgent need to decarbonize the electricity sector, in line with the objectives set by the European Green Deal and the Fit for 55 package, which mandate a reduction in greenhouse gas emissions of at least 55% by 2030 compared to 1990 levels. In this scenario, Italy has transposed the RED II Directive (2018/2001/EU) through Legislative Decree 199/2021, laying the foundations for a massive expansion of Renewable Energy Sources (RES) [1].

Power demand and the limits of anthropized surfaces

According to the Statistical Report 2024 by the Gestore dei Servizi Energetici (GSE), as of December 31, 2024, approximately 37 GW of total photovoltaic capacity is in operation in Italy, of which about 11.5 GW (equal to 31%) is ground-mounted [2]. However, to achieve the targets set by the PNIEC (Integrated National Energy and Climate Plan), a substantial increase in installed capacity is required by 2030. Although regulatory priority is given to the use of built-up surfaces or compromised areas (landfills, quarries, contaminated sites), sector studies demonstrate the insufficiency of such areas. An estimate by Politecnico di Milano, reported in the Position Report of the University of Foggia, highlights that the available disused and infrastructural areas could cover only between 20% and 30% of the new power required to meet national goals [3]. Consequently, the use of portions of agricultural land becomes inevitable to close the energy gap.

Towards agrivoltaics: synergy between electrical and agricultural production

The occupation of agricultural land has historically generated land use competition, leading to the need for solutions that do not subtract land from food production. agrivoltaics fits into this context not as a simple ground-mounted installation, but as an integrated system. The Guidelines of the MASE (Ministry of the Environment and Energy Security) define advanced agrivoltaics as a plant that "adopts innovative integrative solutions with modules mounted above the ground, also foreseeing the

rotation of the modules themselves, in such a way as not to compromise the continuity of agricultural and pastoral cultivation activities" [4]. This approach is confirmed at the international level: a report by the International Energy Agency (IEA) highlights how agrivoltaic systems allow for the optimization of land use (Land Equivalent Ratio > 1), protecting crops from extreme weather events and reducing water requirements thanks to the partial shading of the modules, a critical factor in drought-prone areas such as Southern Italy [5].

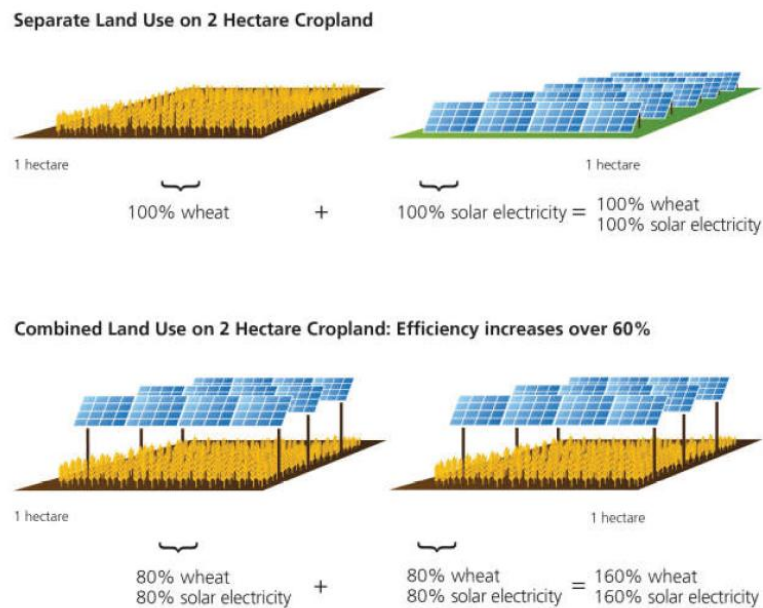


Figure 1 - Conceptual diagram of the Land Equivalent Ratio (LER): comparing land productivity for mono-functional vs. integrated agrivoltaic systems. [6]

1.2. Regulatory definitions and requirements

1.2.1. Distinction between basic and advanced agrivoltaic

The transition from standard ground-mounted photovoltaics to agrivoltaic systems involves a fundamental shift from simple land co-location to a synergistic integration of energy and food production. In the Italian regulatory context, this distinction is formalized through specific guidelines issued by the Ministry of Environment and Energy Security (MASE) and managed by the Gestore dei Servizi Energetici (GSE). While "basic" agrivoltaics represents a commercial evolution designed for efficient dual land use, "advanced" agrivoltaics is framed as an experimental, high-tech solution aimed at digitizing agriculture (*agriculture 4.0*) and monitoring environmental interactions in real-time.

Advanced agrivoltaics and agriculture 4.0

According to the legislative provisions supporting the National Recovery and Resilience Plan (PNRR), an advanced agrivoltaic system is defined as a plant that adopts "innovative integrative solutions with modules mounted above the ground, also foreseeing the rotation of the modules themselves, in such a way as not to compromise the continuity of agricultural and pastoral cultivation activities" [7].



Figure 2 - Advanced AGV [8]

These systems are characterized by the mandatory implementation of a sophisticated monitoring system, which transforms the cultivated field into a data-driven environment. As detailed in the GSE operating rules, the objective is to verify the symbiotic relationship between the PV modules and the crops by tracking specific parameters over time [9]:

1. **Water saving:** monitoring irrigation efficiency and soil moisture retention due to shading effects.
2. **Microclimate and soil fertility:** analyzing changes in temperature, humidity, and the recovery of soil organic content.
3. **Crop productivity and resilience:** verifying the impact of the installation on yield and the system's ability to protect crops from extreme weather events (e.g., heatwaves or hail).

To ensure economic sustainability while gathering scientific data on potential yield losses, the Italian government offers specific incentives (capital contributions up to 40% and feed-in tariffs). In exchange, operators must provide data to the Council for Agricultural Research and Economics (CREA), ensuring that the agricultural revenue is maintained or that electricity production compensates for any yield reduction [7].

Basic agrivoltaics as a commercial standard

In contrast to the highly monitored "advanced" systems, "basic" agrivoltaics is positioned as the scalable commercial successor to traditional ground-mounted PV. While it may lack the extensive sensor networks required for the PNRR incentives, it adheres to the fundamental requirement of preserving the continuity of agricultural activities. By optimizing land use efficiency, often quantified by the Land Area Occupation Ratio (LAOR), basic agrivoltaics addresses the land scarcity issue without the high CAPEX associated with experimental, fully monitored structures[10].



Figure 3 - Standard AGV [11]

Technical requirements: height, density, and continuity

For a system to qualify as "agrivoltaic" (and specifically for the advanced incentives), strict technical constraints are imposed to ensure that energy generation does not supersede agriculture. As summarized in the RSE guidelines for LCA and the GSE regulations [10]:

- **Height of modules:** to guarantee accessibility for farm machinery and livestock, the modules must be elevated. For systems integrated with crop cultivation, the minimum height is typically set to 2.1 m to allow machinery passage. For systems integrated with livestock (zootechnical use), a minimum height of 1.3 m is permitted.
- **Surface occupancy (LAOR):** to prevent shading from inhibiting photosynthesis, the design must limit the Land Area Occupation Ratio. The guidelines recommend that the projection of the modules covers no more than 40% of the total surface area.
- **Agricultural continuity:** the system must guarantee that at least 70% of the total surface area remains available for agricultural use ($S_{\text{agricola}} \geq 0.7 \cdot S_{\text{tot}}$). Furthermore, the electrical production must maintain a minimum specific yield

(at least 60% of a standard PV plant), ensuring the system remains efficient despite agricultural constraints.

1.2.2. Synergies and conflicts of dual land use

The fundamental distinction between standard ground-mounted photovoltaic (GMPV) plants and agrivoltaic systems lies in the philosophy of land utilization. In a conventional ground-mounted PV plant, the land is dedicated exclusively to energy generation. As highlighted in the GSE statistical report 2024, standard installations typically require substantial surface areas (approximately 1.7 hectares per MW in Italy), where the soil is often compacted or covered with gravel to suppress vegetation costs [2]. In these configurations, the spacing between module rows is strictly determined by the need to avoid mutual shading during early morning and late afternoon hours. Consequently, the land between rows remains unproductive "dead space" from an economic perspective, serving only for maintenance access.



Figure 4 - Standard GMPV [12]

Agrivoltaics transforms this paradigm by optimizing the spatial distribution of modules to allow agricultural machinery to operate between or underneath the rows. Although agrivoltaic systems typically require a lower power density (MW/ha) compared to standard PV due to wider row spacing to facilitate light penetration for crops, the overall efficiency of the land use increases. This phenomenon is quantified by the Land Equivalent Ratio (LER). As described in the UNIFG position report, a LER greater than 1 indicates that the combined production of electricity and food on the same land unit exceeds the production achievable by separating the two activities on adjacent plots. For instance, simulations have shown that agrivoltaic systems can achieve LER values up to 1.4–1.7, meaning that 100 hectares of agrivoltaics can produce as much as 140 to 170 hectares of separated land uses, effectively "wasting" only the minimal footprint of the mounting piles [3].

Crop suitability and shading synergies

The integration of PV modules creates a modified microclimate that is not universally beneficial for all agriculture; therefore, crop selection is critical. As noted in the IEA dual land use report and UNIFG studies, shade-intolerant crops (typically C4 plants like corn or sugar beet) may suffer yield losses under high-density PV coverage. Consequently, agrivoltaics is particularly recommended for the recovery of uncultivated land or for "shade-tolerant" (sciaphilous) crops such as lettuce, spinach, potatoes, and berries, which can maintain or even improve yields under partial shading.

In arid or semi-arid contexts, such as Southern Italy, the shading provided by the modules becomes a significant asset. The partial cover reduces direct soil irradiation, leading to a decrease in soil water evaporation and plant evapotranspiration needs. Research cited by RSE indicates that water consumption can be reduced by approximately 20% in agrivoltaic configurations, mitigating drought stress and stabilizing yields during heatwaves [3].

Microclimatic feedback: the cooling effect

The synergy in agrivoltaics is bilateral: while the panels protect the crops, the crops enhance the performance of the PV system. Photovoltaic modules lose efficiency as their operating temperature rises (typically -0.3% to -0.4% efficiency per degree Celsius above standard test conditions). The continuous evapotranspiration from the crops underneath the panels releases latent heat, effectively cooling the surrounding air mass. The UNIFG position report highlights that this "cooling effect" can lower the operating temperature of the modules by several degrees compared to panels installed on bare ground or gravel, resulting in a measurable increase in electrical conversion efficiency. This interaction transforms the agrivoltaic field into a symbiotic system where the vegetation acts as a natural cooling mechanism for the power plant [10].

Structural protection and climate resilience

Finally, the PV structure acts as a passive protection system against extreme weather events, which are becoming more frequent due to climate change. The modules serve as a physical shield, functioning similarly to a discontinuous greenhouse. They protect crops from hail damage, reduce wind speed at the canopy level, and prevent excessive evapotranspiration during peaks of solar irradiance. This protective function allows for the cultivation of higher-value crops in open fields that would otherwise require expensive protective netting or tunnels, thereby offsetting the higher CAPEX of the agrivoltaic mounting structures [13].

1.3. The specific corrosive environment of agrivoltaics

1.3.1. Differences compared to standard PV on sterile ground

The transition from standard ground-mounted photovoltaic (GMPV) plants to agrivoltaic (AGV) systems necessitates a fundamental re-evaluation of the environmental operating conditions for structural components. While solar tracking technology and module efficiency have evolved significantly, the understanding of the underground environment, specifically regarding corrosion dynamics, has often relied on data derived from civil engineering applications in static environments. However, the agrivoltaic context introduces a distinct and significantly more aggressive corrosive environment compared to traditional solar parks.

The baseline: standard PV on "sterile" ground

In standard utility-scale PV installations, the primary objective regarding the ground surface is stability and vegetation suppression to prevent shading. As highlighted in national strategic reports, priority is often given to marginal lands, such as closed landfills, exhausted quarries, or industrial brownfields, where the soil is often compacted, rocky, or covered with gravel layers [3]. In these scenarios, the soil is frequently classified as "undisturbed" or intentionally sterilized. According to the corrosion classifications presented in the GoPV and Eurocode 3 guidelines, undisturbed natural soils are generally characterized by low oxygen availability at depth, resulting in relatively low corrosion rates for galvanized steel piles [14]. In many standard installations, the ground is not subject to mechanical tillage, resulting in a compacted structure that limits the diffusion of oxygen, the primary reactant in the cathodic corrosion reaction, towards the buried metal surfaces. Furthermore, these soils are often arid or possess low moisture retention due to the presence of inert aggregates (gravel/crushed stone), limiting the time of wetness (ToW) on the pile surface.

The agrivoltaic shift: a "living" and aerated electrolyte

Conversely, the Agrivoltaic environment is defined by its "living" nature. The requirement to maintain agricultural continuity transforms the soil from a mere structural support into a chemically active electrolyte. This shift introduces several aggressive factors absent in standard PV:

1. **Soil aeration and disturbance:** unlike the static soil of a standard PV plant, agricultural soil is frequently "disturbed" by tillage, ploughing, and harrowing. As noted in technical training for tracker design, disturbed soils are rich in oxygen and are consequently classified as more corrosive than undisturbed soils [14]. Tillage increases the macroporosity of the soil, facilitating the permeation of atmospheric oxygen (telluric air) deep into the ground [15]. This

high oxygen availability accelerates the depolarization of the cathode in the corrosion cell, significantly increasing the corrosion rate of zinc and steel compared to compacted, anaerobic soils.

2. **Microbial and biological activity:** a unique feature of the agrivoltaic context is the intense biological activity. Agricultural soil is a habitat for a vast mesofauna (e.g., earthworms, nematodes) and microorganisms. Research on durability in farm environments highlights that microbial activity contributes to Microbiologically Influenced Corrosion (MIC) [16]. The metabolic activity of soil bacteria (such as Sulfate-Reducing Bacteria, SRB) and fungi produces organic acids and metabolites that can chemically attack zinc coatings. Furthermore, the presence of earthworms and roots creates channels (biopores) that facilitate water and oxygen infiltration along the pile interface. The introduction of organic carbon fertilizers to stimulate microbial biomass further exacerbates this, as the resulting respiration releases carbon dioxide (CO_2), leading to a local acidification of the soil environment [15].
3. **Chemical complexity and moisture:** while standard PV sites may remain dry for long periods, Agrivoltaic sites are subject to artificial water inputs. The soil acts as a porous medium that retains moisture, essential for crop growth but detrimental to metals. The presence of water transforms the soil into a conductive electrolyte, facilitating ion transfer. Moreover, unlike the inert gravel of a quarry, agricultural soil is chemically altered by the introduction of synthetic and organic compounds (to be detailed in subsequent sections). The position report by the University of Foggia highlights that intensive agriculture involves inputs that alter the soil chemistry, creating a dynamic chemical environment where resistivity and pH fluctuate seasonally, unlike the stable conditions of non-agricultural land[3].

In conclusion, while standard PV structures often reside in a "dormant" geotechnical context, agrivoltaic foundations are immersed in a dynamic, oxygenated, and biologically active reactor. This distinction renders standard corrosion allowances, often calculated for inert soils, potentially insufficient for the specific rigors of the agrivoltaic application.

1.3.2. Impact of agricultural practices: irrigation cycles and fertilizers

The coexistence of photovoltaic structures and agricultural production imposes a radical change in the boundary conditions typically assumed for the durability of underground steel. While standard geotechnical surveys focus on the natural aggressivity of the soil (determined by the native pH and resistivity), the agrivoltaic context involves the artificial introduction of electrolytes (water and fertilizers) and the alteration of the soil's electrochemical balance. This transforms the soil from a static support medium into a dynamic chemical reactor.

Hydrological stress: artificial irrigation and wet/dry cycles

Unlike standard ground-mounted PV plants, which rely solely on natural precipitation and are often sited on arid marginal lands, agrivoltaic sites are characterized by controlled irrigation regimes designed to maintain soil moisture levels suitable for crop growth (typically between 50% and 80% of field capacity). As outlined in the GSE monitoring guidelines, the implementation of efficient irrigation systems is often a prerequisite for advanced agrivoltaic incentives to ensure agricultural continuity [9].

However, this practice fundamentally alters the corrosion kinetics of buried structures. The introduction of irrigation water increases the Time of Wetness (ToW) of the pile surface. According to the corrosion mechanisms described in the Geopalitalia Manual (referencing DIN 50929-3), the presence of moisture lowers the soil resistivity, facilitating the flow of ionic currents between anodic and cathodic areas on the metal surface [17]. More critically, agricultural irrigation induces frequent wet/dry cycles. This cyclicity is far more detrimental than constant immersion. During the "dry" phase (or water recession), atmospheric oxygen penetrates the porous soil matrix, replenishing the cathodic reactant (O_2) at the metal interface. During the subsequent "wet" phase, the water acts as an electrolyte, reactivating the corrosion cell. This mechanism, known as the differential aeration cell (or macrocell), is particularly aggressive in the top 30-50 cm of the soil (the "transition zone") [15]. Here, the fluctuation of the water content is most intense due to evaporation and root absorption, leading to corrosion rates that can be significantly higher than those observed in undisturbed, deep soil.

Chemical stress: fertilizers and soil acidification

The application of fertilizers introduces soluble salts into the soil, which dissociate into ions, drastically increasing the electrical conductivity of the soil solution. Based on the analysis of degradation phenomena in concrete and steel structures in agricultural environments, the primary corrosive agents introduced via fertilization are [18]:

1. **Nitrogenous fertilizers (N):** these are the most common inputs in agriculture, often applied as urea ($(NH_2)_2CO$) or ammonium nitrate (NH_4NO_3). The hydrolysis of urea releases ammonia (NH_3) and carbon dioxide (CO_2). Crucially, the subsequent nitrification process (the biological oxidation of ammonia to nitrite followed by the oxidation of nitrite to nitrate) releases hydrogen ions (H^+), leading to a localized acidification of the soil (lowering pH) [15]. Acidic environments destabilize the protective zinc carbonate film (patina) formed on hot-dip galvanized steel, accelerating the dissolution of the zinc coating.
2. **Sulfates (SO_4^{2-}):** often introduced via potassium sulfate (K_2SO_4) or Superphosphates to support plant growth. Sulfates are aggressive towards both zinc and concrete foundations. In anaerobic conditions (compacted deep soil),

Sulfate-Reducing Bacteria (SRB) can reduce sulfates to sulfides (S^{2-}), causing severe localized pitting corrosion [19].

3. **Potassium (K) and chlorides (Cl):** potassium chloride (KCl) is a standard fertilizer. Chloride ions are small and highly mobile; they possess the ability to penetrate the passive films of metals, initiating pitting corrosion. Even in the absence of chlorides, the high ionic concentration resulting from K-fertilization decreases soil resistivity, which is linearly correlated with increased corrosion rates [17].

Agrochemical load and long-term accumulation

The intensity of the chemical attack is defined by the frequency of application. In intensive agriculture (e.g., vineyards or orchards compatible with elevated agrivoltaics), treatments are recurrent. Typical annual loads can reach significant levels of nitrogen and sulfur, creating a permanently aggressive environment that standard "rural" atmospheric corrosion models (ISO 9223) do not account for.

Furthermore, in organic farming, which is often preferred in agrivoltaic projects for marketing synergy, copper-based fungicides (e.g., bordeaux mixture) are frequently used. The accumulation of copper ions (Cu^{2+}) in the soil poses a severe threat to galvanized piles due to displacement plating: since copper is more noble than zinc in the galvanic series, copper ions in the soil solution can plate out onto the zinc surface [18]. This creates disjointed micro-cathodes that drive rapid galvanic corrosion of the surrounding zinc, leading to premature consumption of the protective layer.

1.3.3. Influence of agrochemicals (pesticides) on soil aggressivity

In addition to the hydrological stresses (wet/dry cycles) and nutrient loading (fertilizers) discussed in previous sections, the agrivoltaic environment introduces a unique and often underestimated class of chemical agents: phytosanitary products (pesticides, herbicides, and fungicides). Unlike standard ground-mounted PV plants, which are typically located on marginal, industrial, or sterile lands where vegetation is suppressed, agrivoltaic structures are immersed in an active agricultural ecosystem subject to periodic chemical treatments. These commercial formulations are rigorously tested to ensure low "phytotoxicity" (safety for plants) and environmental biodegradability, but their chemical compatibility with metallic structural elements is rarely evaluated by manufacturers. This creates a "blind spot" in standard durability assessments, where the contact between these organic/inorganic compounds and the zinc coating of the piles can lead to unexpected corrosion phenomena [15].

Chemical composition and metallurgical incompatibility

The primary risk arises from the proximity of the mounting structure to the crop canopy. During foliar application (spraying), the steel piles are inevitably exposed to spray drift and to the accumulation of residues in the soil immediately surrounding

the foundation (the "dripline" effect). Two main categories of compounds commonly used in integrated and organic farming present significant threats to galvanized steel:

1. **Copper-based fungicides (the "displacement" effect):** copper salts, such as copper sulfate (CuSO_4 , known as "bordeaux mixture") or copper oxychloride, are widely used to control fungal diseases like downy mildew, particularly in vineyards and orchards. While effective for crops, copper presents a severe electrochemical threat to zinc. According to the galvanic principles outlined in the Romanoff investigations and DIN 50929-3, copper is electrochemically more noble than zinc ($E^0_{\text{Cu}} > E^0_{\text{Zn}}$). When copper ions (Cu^{2+}) wash into the soil solution, they can undergo a displacement reaction upon contact with the pile, plating out as metallic copper on the zinc surface [19], [20]. This formation creates microscopic "external cathodes" (classified as factor Z_{15} in DIN 50929-3) directly on the zinc coating, driving rapid localized pitting corrosion of the surrounding zinc. German field studies on vineyard soils indicate that long-term application can lead to copper accumulation in the topsoil, creating a permanent galvanic stress that exceeds standard soil corrosivity models [21].
2. **Sulfur and acidifying compounds:** elemental sulfur is a common fungicide and acaricide. In the soil environment, sulfur is biologically oxidized by *Thiobacillus* bacteria into sulfuric acid (H_2SO_4). This process leads to a localized reduction in pH around the pile. As demonstrated in the Romanoff NBS Circular 579, soils with high acidity (low pH) or containing "cinders" (which release sulfur compounds) are among the most aggressive towards steel, causing severe pitting rates. Furthermore, herbicides often utilize surfactants and salts to improve leaf adhesion. These additives increase the ionic conductivity of the soil moisture film. As noted in electrochemical studies regarding the DIN 50929-3 W_0 factor, an increase in sulfate concentration in the electrolyte significantly lowers the corrosion resistance of unalloyed and galvanized steels [19], [20].

Persistence and accumulation in the transition zone

A critical factor distinguishing agrochemicals from simple water exposure is their persistence. While water evaporates, the heavy metal components of pesticides (like copper) do not degrade; they accumulate in the top 30-50 cm of the soil, precisely the critical transition zone for the structural piles. Literature regarding vineyard soils in Europe indicates that decades of fungicide application can result in copper concentrations exceeding 100-200 mg/kg in the topsoil [21]. For an agrivoltaic plant with a projected lifespan of 25-30 years, this implies that the piles are not installed in a static chemical environment, but in a medium where the concentration of corrosive agents will progressively increase, potentially shifting the soil classification from "weakly aggressive" to "highly aggressive" over time.

2 Chapter 2: structural technologies and materials

2.1. Structural typologies

2.1.1. Fixed-tilt structures vs. single-axis trackers

The structural design of photovoltaic (PV) plants is the fundamental determinant of both energy yield and land compatibility. In the context of large-scale solar power, and specifically within the emerging agrivoltaic sector, two primary mounting typologies are debated: static fixed-tilt structures and dynamic tracking systems. While the former represents the historical standard for reliability and simplicity, the latter has become the dominant technology for utility-scale projects due to its superior Levelized Cost of Electricity (LCOE) performance.

Fixed-tilt structures

The fixed-tilt configuration characterizes the early generations of ground-mounted PV and remains a viable solution for specific applications where maintenance simplicity is paramount. In this topology, PV modules are mounted on a stationary steel racking system, typically supported by two parallel rows of piles (driven or screw piles) for every table to ensure stability against wind and snow loads. The modules, usually arranged in groups of 2, 3, or 4 in landscape or portrait orientation, are permanently oriented towards the equator (South in the Northern hemisphere) to maximize annual irradiation capture.



Figure 5 - Fixet structure type [22]

The selection of the tilt angle is a critical design parameter. As defined in the GSE Operating Rules for the calculation of the reference yield, the optimal inclination is typically set equal to the local latitude minus approximately 10 degrees (30°–35° in Italy) to maximize the collection of direct irradiation during the summer months when the sun is higher, while avoiding mutual shading between rows during winter [9]. From an operational perspective, fixed systems offer the highest reliability due to the absence of moving parts, reducing the risk of electromechanical failures. However, their energy generation profile is peaked at solar noon, with significantly lower production during the early morning and late afternoon hours compared to tracking systems [23].

Single-axis trackers (SAT)

Currently, horizontal single-axis trackers (HSAT) represent the preferred solution for utility-scale and agrivoltaic installations. Unlike fixed structures, SATs rotate the PV modules around a single North-South axis, following the sun's path from East to West. This movement allows the angle of incidence of solar rays to remain near-perpendicular to the module surface for a longer duration throughout the day [24]. The primary advantage of SATs is the significant increase in specific productivity. Literature reviews indicate that SAT systems can achieve energy yield gains ranging from 15% to 25% compared to fixed-tilt counterparts, depending on the latitude and local albedo conditions [23]. This gain is primarily concentrated in the morning and evening hours, resulting in a broader generation curve that better matches electricity demand profiles.

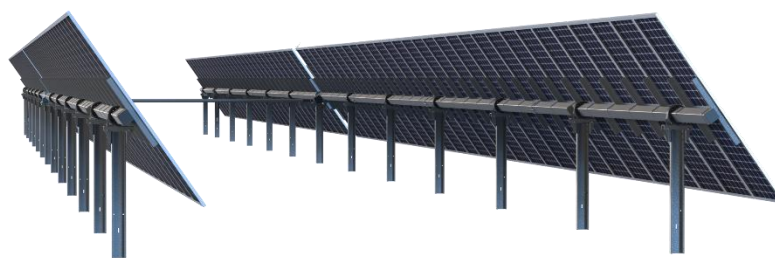


Figure 6 - Single-axis tracker structure type [25]

Structurally, SATs are generally supported by a single row of piles per tracker row, reducing the ground footprint and potentially facilitating the passage of agricultural machinery between rows (inter-row agrivoltaics). The modules are mounted on a rotating torque tube actuated by electric motors. Common configurations include the 1P (one module in portrait) or 2P (two modules in portrait stacked vertically), with the 1P configuration often preferred in bifacial agrivoltaic applications to minimize

backside structural shading. However, the introduction of movement adds complexity. SATs require sophisticated control algorithms (including backtracking strategies to prevent row-to-row shading during low solar elevation) and active stow positions to protect the structure against high winds. This introduces potential failure modes related to the actuation mechanism (motors, gearboxes) and control electronics, necessitating a more rigorous operation and maintenance (O&M) protocol compared to fixed systems [24].

Dual-axis trackers

Dual-axis trackers (DAT) represent the most technologically advanced solution, capable of tracking the sun's position across both the azimuth (East-West) and zenith (elevation) axes. This capability allows the modules to maintain perfect alignment with the sun vector at all times, theoretically offering yield increases of 25-35% over fixed systems, particularly in high latitudes.



Figure 7 - Dual-axis tracker structure type [26]

In the agrivoltaic sector, specific DAT designs have been experimented with, such as the elevated systems developed by Rem Tec (Agrovoltaico®). These structures feature widely spaced axes (up to 12-14 m) and high clearance (> 5 m) to allow full agricultural maneuverability underneath. Despite their high efficiency and agricultural compatibility, DATs are currently less common in industrial-scale projects due to their significant structural complexity, high CAPEX (Capital Expenditure), and the increased wind loading susceptibility of the large "sails" created by the tracker tables[23] ,[3].

2.1.2. Tracker mechanics: backtracking and stow position

The implementation of single-axis trackers (SAT) in agrivoltaic systems introduces a layer of mechanical and control complexity significantly higher than that of standard ground-mounted plants. While the primary function of a tracker is to minimize the angle of incidence between the solar vector and the module normal to maximize energy yield, the dual use of land imposes additional kinematic constraints related to structural safety, machinery accessibility, and agronomic light management.

Actuation and backtracking algorithms

Modern SATs are typically actuated by DC motors or independent self-powered drives that rotate the torque tube along the North-South axis. The rotation speed is generally low during standard tracking ($<1^\circ/\text{min}$) to follow the astronomical path of the sun. However, the actuation system must be capable of rapid rotation (up to $5^\circ/\text{s}$ – $10^\circ/\text{s}$) to reach safety positions (stow) during sudden extreme weather events [23].

In standard utility-scale PV, backtracking is a geometric control strategy used during the early morning and late afternoon hours when the sun is low on the horizon. To prevent mutual shading between adjacent rows, the trackers deviate from the perfect solar alignment, rotating towards a flatter position. While this reduces the direct irradiance component on the module, it prevents the electrical mismatch losses caused by inter-row shading, which are disproportionately detrimental to string performance [23]. In the context of agrivoltaics, backtracking evolves from a purely electrical optimization tool into an agro-ecological management instrument. Advanced backtracking algorithms, such as those analyzed by Casares de la Torre et al., are designed to account for the presence of tree crops or hedgerows between rows. These "slope-aware" and "obstacle-aware" algorithms adjust the tracking angle not only to avoid module-on-module shading but also to manage the shadow cast by the crop canopy onto the modules and vice-versa, optimizing the global Land Equivalent Ratio (LER) rather than just the electrical yield [27].

Safety strategies: stow positions for wind and snow

The structural stability of trackers is critical, particularly for agrivoltaic systems which may feature elevated structures (mounting height >2.1 m) or wider row spacing, altering the aerodynamic coefficients compared to standard low-mount PV.

- **Wind stow:** high wind speeds induce torsional galloping and aeroelastic instability. As detailed in failure analysis literature, when wind speeds exceed a critical threshold (typically 12–16 m/s), the system enters "stow mode." The traditional stow position is horizontal (0°), but recent dynamic wind analyses suggest that a high-tilt position (e.g., 30° – 45°) may be more stable against torsional flutter for certain structural designs [24].
- **Snow stow:** in the event of heavy snowfall, the trackers must adopt a position that facilitates shedding to prevent mechanical overload. This is typically a maximum tilt angle. Conversely, during light snow or hail events, a specific stow angle might be adopted to minimize the impact energy of hailstones on the glass surface, protecting the module integrity [24].

Agricultural interaction: accessibility and light management

A defining feature of advanced agrivoltaic trackers is the integration of control logic dedicated to farming operations. To ensure the continuity of agricultural activities, a mandatory requirement for national incentives (e.g., PNRR in Italy), the tracking system must facilitate the passage of heavy machinery (tractors, harvesters). Modern trackers are equipped with "farming mode" or "cleaning mode" positions, often commandable via remote apps or SCADA systems by the operator. This function rotates the modules to a specific angle (often vertical or horizontal depending on the clearance required) to maximize the inter-row width, allowing tractors to pass without risking collision with the torque tube or module edges [3].

Furthermore, the tracking strategy can be modified to favor agronomic development over energy production ("eco-voltaic" tracking). For shade-intolerant crops or during phenological phases requiring high irradiation (e.g., flowering or fruit setting), the panels can be deviated from the sun vector to minimize shading on the crop strip. Conversely, during heatwaves, the panels can track to maximize ground shading, reducing soil evapotranspiration and protecting crops from sunburn. Although these strategies may result in a sub-optimal Levelized Cost of Electricity (LCOE) due to the deliberate sacrifice of solar yield, they are essential to satisfy the regulatory requirement of maintaining a Gross Saleable Production (PLV - Produzione Lorda Vendibile) comparable to the pre-installation baseline, ensuring the project remains legally classified as an agrivoltaic system rather than an industrial solar park [10], [4].

2.2. Metallic materials

2.2.1. Hot-dip galvanized steel (ISO 1461 / ISO 10346)

Hot-dip galvanizing (HDG) represents the cornerstone of corrosion protection for agrivoltaic steel structures. The fundamental principle relies on the formation of a physical barrier that isolates the steel from the corrosive soil and atmospheric environment, coupled with the electrochemical (sacrificial) protection provided by zinc, which is anodic relative to iron. However, within the structural engineering of PV plants, two distinct manufacturing processes are employed depending on the component's function and thickness: general (batch) galvanizing and continuous galvanizing. Understanding the metallurgical and morphological differences between these two is critical for predicting the durability of components, particularly at connection points and soil interfaces.

1. General batch hot-dip galvanizing (ISO 1461)

For primary structural elements such as the main vertical piles (typically "H", "C", or "Ω" profiles with thicknesses exceeding 3–4 mm) and custom-welded assemblies, the

standard treatment is batch hot-dip galvanizing, governed by ISO 1461. This process involves immersing the fully fabricated steel article into a bath of molten zinc.

The process phases and surface preparation: the batch process is sequential and requires meticulous surface preparation to ensure the metallurgical bonding of zinc to steel. As detailed in Steel Metallurgy (Vol. 2) and the technical literature, the process consists of the following critical stages:

- a. **Degreasing:** removal of organic contaminants, oils, and grease using alkaline or acidic solutions.
- b. **Pickling:** immersion in dilute hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) to remove surface rust and mill scale (iron oxides). Proper pickling is mandatory because zinc will not react with an oxidized steel surface [18].
- c. **Fluxing:** the steel is dipped in a flux solution (typically zinc ammonium chloride). This layer prevents flash oxidation before dipping and promotes wetting by the molten zinc.
- d. **Galvanizing:** the dried profile is immersed in a bath of molten zinc at approximately $440^{\circ}C - 460^{\circ}C$ [28].
- e. **Cooling:** Upon withdrawal, the zinc solidifies.

Metallurgical layer formation (Fe-Zn Phases): a defining characteristic of batch galvanizing is the formation of a diffusion coating. During the immersion (which lasts several minutes), a reaction occurs between the liquid zinc and the solid iron, creating a series of intermetallic Fe-Zn layers growing outwards from the steel interface [18]:

- **Gamma Phase (Γ):** thin, hard layer at the steel interface (21–28% Fe).
- **Delta Phase (δ):** compact layer (7–11% Fe), tough and resistant.
- **Zeta Phase (ζ):** columnar crystals (6% Fe).
- **Eta Phase (η):** the outer layer of pure zinc (solidified bath metal).

Crucially, the inner alloy layers are harder than the base steel (up to 250 HV for the Delta phase vs. 150 HV for standard steel) [17]. This provides exceptional abrasion resistance during the transport and pile-driving phases, preventing the coating from stripping off when the pile is driven into abrasive soils containing gravel or stones.

Thickness requirements: main piles vs. secondary profiles: the protective thickness required by ISO 1461 is not uniform but varies according to the steel section thickness (t). This distinction is vital for agrivoltaic structures, which utilize heavy gauge steel for piles and lighter gauges for mounting rails or diagonal bracing.

- **Main vertical piles ($t \geq 3$ mm):** for the primary supports, the standard mandates a mean coating thickness of $70 \mu m$ (local minimum $55 \mu m$) for steel between 3

mm and 6 mm. For thicker sections ($t > 6$ mm), the requirement increases to 85 μm [28].

- **Secondary profiles** ($1.5 \text{ mm} \leq t < 3 \text{ mm}$): for lighter structural elements, such as horizontal purlins or diagonal braces, which often have thicknesses around 1.5 mm, the standard requires a thinner coating to avoid brittleness. In this range, ISO 1461 mandates a mean coating thickness of 55 μm (local minimum 45 μm) [28], [29].
- **Thin gauge elements** ($t < 1.5 \text{ mm}$): for very thin components, the mean thickness requirement is further reduced to 45 μm [28].

It is important to note that actual achieved thicknesses on batch-galvanized piles are often higher (85–100 μm) depending on the silicon content of the steel (Sandelin effect), providing a substantial corrosion allowance for long-term underground durability[30].

Continuous galvanizing (pre-galvanized coils - ISO 10346)

Secondary structural elements (purlins, mounting brackets, and lighter tracker components) are frequently manufactured using pre-galvanized steel coils. This material is processed according to ISO 10346 (formerly) [31] in continuous galvanizing lines.

Process differences and the "uncoated edge" issue: in this process, the steel coil is unwound and passes rapidly through the molten zinc bath. Unlike batch galvanizing, the immersion time is very short (seconds), which suppresses the growth of the brittle Fe-Zn alloy layers, resulting in a more ductile coating suitable for subsequent forming. However, the most critical distinction for agrivoltaic design lies in the sequence of operations. In continuous galvanizing, the steel coil is coated before being cut to length, punched, or drilled to form the final profile. Consequently, all cut edges and the internal surfaces of punched holes remain bare steel, completely devoid of the zinc coating.

Corrosion implications at connections: unlike batch galvanizing (ISO 1461) [28], where the part is dipped after fabrication, ensuring that edges, holes and welds are fully encapsulated, profiles made from pre-galvanized coils rely entirely on the cathodic protection (sacrificial action) of the zinc on the adjacent faces to protect the exposed steel core. While zinc can electrochemically protect bare steel over small distances (typically up to 1-2 mm depending on the electrolyte conductivity), this mechanism has physical limits.

- **Throwing power:** in arid environments or low-conductivity soils, the "throwing power" of the galvanic current is limited. If the steel thickness is significant (e.g., $> 2.5 \text{ mm}$), the distance from the zinc surface to the center of the

cut edge may be too great for effective galvanic throwing, leading to the formation of red rust at the center of the cut.

- **Coating mass limitation:** standard continuous coatings are often specified with lower masses compared to batch galvanizing (e.g., Z275 [31], approx. 20 μm), providing a smaller reservoir of sacrificial zinc.

Therefore, while pre-galvanized profiles (ISO 10346) offer economic advantages and tighter dimensional tolerances, their use in the splash zone or underground requires careful verification to ensure that the unprotected edges do not become initiation points for severe localized corrosion, particularly in the aggressive agrivoltaic soil environment described in previous chapters.

2.2.2. Zn-Al-Mg alloys: self-healing and ammoniacal resistance

The evolution of coating technologies for steel structures in solar applications has led to the development of ternary alloys based on zinc, aluminum, and magnesium (ZM). These materials, governed by the standard ISO 10346, represent a significant technological shift from traditional batch hot-dip galvanizing (HDG) and standard continuous galvanizing (Z). While traditional zinc coatings rely primarily on the thickness of the layer to provide barrier and sacrificial protection, ZM alloys utilize a modified chemical composition to alter the thermodynamics and kinetics of the corrosion reaction, offering superior performance with reduced coating masses. This is particularly relevant for agrivoltaic structures formed from cold-rolled coils, where the protection of cut edges and resistance to agricultural chemicals are critical design factors.

Commercial compositions and manufacturing processes

The ZM alloy family is characterized by the addition of magnesium (1–3%) and aluminum (1–11%) to the zinc bath. In the specific context of the European photovoltaic market, two primary commercial formulations are frequently employed: Magnelis®, developed by ArcelorMittal and Topcor®, developed by Wuppermann (often associated with the WZM product line).

Magnelis® is produced via a continuous hot-dip galvanizing process. Its chemical composition is rigorously defined as 93.5% Zinc, 3.5% Aluminum, and 3% Magnesium [32]. This specific ratio was selected to optimize the formation of a stable ternary eutectic phase. The material is typically supplied in coils, which are subsequently uncoiled, cut and cold-formed into structural profiles (such as C-piles or Ω sections). Topcor®, and the associated range of products manufactured by Wuppermann, utilizes a similar ZM alloy concept but is often distinguished by manufacturing technology. While standard continuous galvanizing applies the coating to a wide strip which is later slit (leaving exposed edges), specific processes employed by manufacturers like Wuppermann allow for the galvanizing of slit strips

or the application of the coating in a way that ensures high-integrity coverage. A distinctive feature of the Topcor®/WZM approach in tubular or closed profile production is the ability to ensure protection that mimics a post-galvanized integrity on a pre-galvanized product, relying heavily on the alloy's capability to protect the heat-affected zones and longitudinal welds [33].

Unlike batch galvanizing (ISO 1461), where the steel is dipped after forming, ZM profiles are formed from pre-coated coils. This implies that the cut edges (perforations, shearing lines) expose the steel substrate. The viability of these profiles for underground use depends entirely on the unique electrochemical properties of the ZM alloy to bridge this gap.

Microstructure and phase formation

The superior corrosion resistance of ZM alloys is derived from their unique solidification microstructure. Unlike the pure zinc (η -phase) outer layer of standard galvanized steel, the ZM coating solidifies into a complex multiphase structure. As detailed in metallurgical analyses of ternary coatings, the microstructure consists of primary zinc grains embedded in a matrix of binary eutectic ($Zn-MgZn_2$) and ternary eutectic ($Zn-Al-MgZn_2$) phases [21], [32]. The presence of the intermetallic phase $MgZn_2$ is crucial. It is harder than pure zinc, providing improved abrasion resistance during pile driving operations. Furthermore, this complex microstructure creates a tortuous path for corrosive electrolytes. The corrosion products must navigate through the stable eutectic network, significantly slowing down the oxidation rate of the underlying coating compared to the linear dissolution of a pure zinc layer.

The self-healing mechanism on cut edges

The defining characteristic of ZM alloys is their ability to repair exposed steel at cut edges, a phenomenon known as "self-healing." While standard zinc provides galvanic protection, the range of this protection (throwing power) is limited, and the consumption of zinc at the edge can be rapid. In ZM alloys, the mechanism is chemically distinct. When the cut edge is exposed to moisture (electrolyte), the initial corrosion of the magnesium-rich phases releases magnesium ions (Mg^{2+}) into the solution. These ions alter the local pH and facilitate the precipitation of dense, stable corrosion products. Specifically, studies have shown that ZM alloys promote the formation of simonkolleite ($Zn_5(OH)_8Cl_2 \cdot H_2O$) and zinc hydroxysulfates, which are far more compact and insoluble than the loose zinc oxide/hydroxide ($ZnO/Zn(OH)_2$) formed on standard galvanized steel [32]. This dense "cement-like" layer creates a physical barrier that seals the cut edge, arresting further dissolution of the sacrificial coating. Field tests cited in technical literature demonstrate that red rust on ZM cut edges typically appears briefly before being covered by this white healing film, whereas standard zinc edges may continue to corrode [34].

Resistance in agricultural and ammoniacal environments

Agrivoltaic structures are subjected to environmental stressors absent in standard solar parks, most notably ammonia (NH_3) derived from livestock manure and nitrogen-based fertilizers. Ammonia is highly aggressive towards zinc, as it can form soluble zinc-ammine complexes ($[Zn(NH_3)_4]^{2+}$), leading to rapid stripping of the protective layer. Research comparing Z and ZM coatings in ammoniacal environments indicates that the magnesium content plays a stabilizing role. The corrosion products formed on ZM alloys in alkaline, ammonia-rich environments (typical of farm soils) are more stable than those on pure zinc. Accelerated corrosion tests involving ammonium sulfate have shown that ZM coatings exhibit mass loss rates significantly lower than standard hot-dip galvanized samples [35]. Furthermore, the enhanced resistance to chloride-induced corrosion makes ZM alloys particularly suitable for soils treated with potassium chloride fertilizers. The magnesium ions stabilize the passivation film even in the presence of chlorides, preventing the breakdown that typically leads to pitting in standard galvanized piles.

Comparison with hot-dip galvanizing (HDG)

The use of ZM alloys offers a paradigm shift in structural design. Standard HDG piles (ISO 1461) rely on a high coating mass (typically 50–85 μ m) to guarantee durability. In contrast, ZM coatings can achieve equivalent or superior service lives with significantly lower thicknesses (typically 20–25 μ m, corresponding to ZM310 or ZM430 grades). This reduction in coating mass has positive implications for sustainability, reducing the consumption of zinc and the carbon footprint of the structure. However, for the specific application of underground piles, care must be taken regarding the "transition zone". While the self-healing is effective, the total reservoir of sacrificial material is lower in a 25 μ m ZM coating compared to an 85 μ m HDG coating. Therefore, in soils with extremely low resistivity or high acidity, the long-term depletion rate of the thinner ZM layer must be carefully modeled against the claimed reduction in corrosion velocity [21], [32].

2.2.3. Weathering steel (Corten): limitations in buried applications

Weathering steel, commercially and historically known as "Corten" (derived from corrosion resistance and tensile strength), represents a class of high-strength low-alloy (HSLA) steels that has historically seen limited use in the utility-scale photovoltaic sector compared to hot-dip galvanized steel. However, its adoption is currently expanding within the agrivoltaic sector. This trend is primarily driven by landscape integration requirements imposed by heritage and environmental superintendencies. The material's characteristic maturation leads to a chromatic shift from bright orange to a dark, warm brown, which blends more harmoniously with agricultural landscapes and rural tones compared to the metallic reflectivity of zinc.

While weathering steel offers excellent performance in atmospheric environments classified as C2 or C3 (urban/rural), its behavior changes drastically when buried, necessitating specific engineering considerations for the foundation design.

Chemical composition and metallurgical grades (ISO 10025-5)

The enhanced atmospheric corrosion resistance of weathering steel (typically 5 to 8 times higher than conventional carbon steel) is achieved through specific alloying elements, primarily copper, chromium, nickel, and phosphorus. According to the standard ISO 10025-5, these steels are classified into different grades, the most common being:

- **Corten A (S355J0WP):** characterized by a high phosphorus content (0.07 to 0.15%). This grade maximizes the formation of the protective patina and is often preferred for architectural applications where aesthetic quality is paramount. However, the high phosphorus content can reduce impact toughness and weldability [35].
- **Corten B (S355J0W/J2W):** characterized by a lower phosphorus content (less than 0.035%) and often alloyed with vanadium. This grade maintains good corrosion resistance while offering superior mechanical properties and impact strength at lower temperatures, making it more suitable for structural components subjected to heavy dynamic loads, such as the torque tubes and main piles of solar trackers [35].

For agrivoltaic structures, the choice typically falls on grades that balance structural integrity with the aesthetic requirement of the protective oxide layer.

Mechanism of patina formation and acceleration

The protective mechanism of weathering steel relies on the formation of a dense, adherent, and stable oxide layer known as the patina. Unlike the porous and non-protective rust formed on carbon steel (composed mainly of non-adherent iron oxides), the patina on weathering steel is enriched with copper, chromium, and phosphorus. These elements foster the formation of an inner layer of amorphous oxyhydroxides (such as α -FeOOH substituted with Cr) that acts as a barrier against the ingress of oxygen and moisture [36].

Crucially, the correct development of this patina requires specific environmental cycles: the steel must undergo alternating periods of wetting and drying (wet/dry cycles). During the dry phase, the oxide layer dehydrates and consolidates, becoming impermeable. In industrial practice, the natural formation of a stable dark-brown patina can take several years (typically 1 to 3 years) depending on the exposure conditions. Since agrivoltaic plants are often subject to strict visual delivery constraints, manufacturers frequently employ chemical etching treatments (accelerating solutions) to induce the oxidation process rapidly before installation [15].

Economic and regulatory perspective

From an economic standpoint, weathering steel presents a competitive alternative to galvanized steel. Although the base material cost may be slightly higher, it eliminates the need for hot-dip galvanizing. This advantage is particularly pronounced when landscape regulations mandate a brown or earthy coloration. Achieving a similar aesthetic with galvanized steel would require a duplex system (galvanizing plus powder coating or liquid painting). According to ISO 12944, such painting systems entail significant additional costs and introduce maintenance requirements, as the organic coating degrades over time due to UV exposure, whereas the Corten patina regenerates itself if scratched [37].

Limitations in soil and underground corrosion

Despite its superior atmospheric performance, weathering steel is not intrinsically resistant to soil corrosion. The fundamental requirement for patina stabilization, the wet/dry cycle, is often absent in underground environments.

In the subsoil, particularly in clay-rich or waterlogged agricultural soils, the steel remains continuously damp. Under these conditions of permanent wetness and limited aeration, the stable protective oxide cannot form. Instead, the corrosion mechanism reverts to that of standard carbon steel, or may even be accelerated due to the galvanic coupling with the noble alloying elements (Cu) if they do not form a passivation layer. As noted in geotechnical corrosion studies, weathering steel in soil behaves similarly to carbon steel, with corrosion rates that can range from 0.05 to 0.20 mm/year depending on soil resistivity, pH, and chloride content [15].

Furthermore, the presence of chlorides (from fertilizers or saline groundwater) can destabilize the patina, leading to the formation of akaganeite (β -FeOOH), a non-protective and expansive corrosion product that promotes localized pitting [18]. This makes the material particularly vulnerable in the agronomic environment described in previous chapters.

Consequently, the use of weathering steel piles in agrivoltaics requires a hybrid protection strategy. The portion of the pile embedded in the ground, including the transition zone at the soil-air interface (typically the first 30-50 cm above ground), must be protected. Common solutions include:

- **Sacrificial allowance:** increasing the thickness of the steel to account for the expected material loss over the project's lifetime (25-30 years). However, this approach is often insufficient or uneconomical in aggressive agricultural soils.
- **Bituminous/epoxy coatings:** applying a heavy-duty barrier coating to the underground section.

- **Concrete encasement:** casting the pile foundation in concrete to provide an alkaline environment that passivates the steel, leaving only the above-ground portion exposed to develop the aesthetic patina.

Without these measures, using the atmospheric corrosion rates defined in ISO 9223 [38] to predict underground durability would lead to a gross underestimation of material loss, risking structural failure.

2.3. Foundation systems

2.3.1. Direct driven piles (ramming) and the steel concrete interface

The structural stability of an agrivoltaic plant relies entirely on the interaction between the steel superstructure and the soil. Unlike traditional civil engineering works where foundations are often massive and rigid (e.g., reinforced concrete footings), photovoltaic plants typically utilize deep foundations that must resist complex loading scenarios. These include significant uplift forces caused by wind suction on the modules, compressive loads from snow and structural dead weight and horizontal shear forces. The selection of the foundation typology is strictly dictated by the soil stratigraphy, the environmental corrosivity class, and the legislation requirements.

Direct driven piles (ramming) and installation techniques

Currently, the industry standard for utility-scale and basic agrivoltaic plants is the direct driven pile, commonly referred to as ramming. In this process, open steel profiles (typically "C", "Ω", or "H" sections) are driven directly into the ground using hydraulic hammers mounted on tracked pile-driving machines. The primary advantage of this technique is the densification of the soil surrounding the pile. Unlike drilling methods, which remove soil and potentially decompress the borehole walls, ramming displaces the soil radially. This displacement increases the lateral earth pressure ($K_0 \rightarrow K_p$) and, consequently, the skin friction contributing to the bearing capacity. For standard ground-mounted PV plants, the piles are typically driven to a depth of 2.0 to 3.0 m, depending on the site-specific pull-out requirements verified during the campaign. In these standard configurations, a single continuous pile serves as both the foundation and the above-ground support for the racking system.

However, elevated agrivoltaic systems, which require clearance heights exceeding 2.1 m to facilitate the passage of tractors and harvesters, present a logistical challenge for standard pile drivers due to limited mast heights. To address this, a split-pile configuration is often adopted. In this method, the foundation pile (the underground section) is driven first until its head protrudes slightly above ground level. Subsequently, the elevation column (the above-ground section) is bolted onto the foundation head at a height of approximately 0.5 – 1.0 m. This segmentation allows for

the use of standard driving machinery while achieving the necessary structural height required for agricultural operations.

Drilling and concrete backfill

In soils containing high percentages of gravel, cobbles, or shallow bedrock (refusal layers), direct driving becomes impossible or risks causing severe buckling of the steel profile. In such geotechnical contexts, pre-drilling is mandatory. As documented in recent field reports, such as those for the Vercelli site, the procedure involves drilling a borehole (typically 300-500 mm in diameter) to the required depth. The steel profile is then inserted into the void, and the annulus is backfilled with concrete or a self-compacting cementitious grout. This effectively creates a micropile, where the load transfer mechanism shifts from direct steel-soil friction to the friction between the concrete bulb and the rough borehole walls. This method ensures structural continuity in heterogeneous soils where driven piles would fail to reach the design depth [39].

Pull-out testing protocols

To validate the design assumptions regarding soil stiffness and strength, pull-out tests (POT) are mandatory during the preliminary engineering phase. These tests determine the ultimate bearing capacity of the pile under three critical load components:

1. **Axial tensile load (uplift):** this simulates wind suction, which is often the governing design load for PV structures due to the "sail effect" of the panels.
2. **Axial compression load:** this simulates the combined weight of snow, the structure itself, and the modules.
3. **Horizontal (shear) load:** this evaluates the lateral stiffness and the resistance to overturning moments.

According to the testing procedures described in technical reports and the NTC 2018 standards, the test pile is instrumented with high-precision digital comparators or linear variable differential transformers (LVDTs) to measure displacement relative to an independent reference beam. The load is applied incrementally using a hydraulic jack that reacts against a contrast beam or the dead weight of an excavator. The failure criterion is typically defined by a limiting displacement (e.g., vertical displacement >10-20 mm) or by the inability of the pile to sustain a load increment (creep failure). The geotechnical design is then calibrated to ensure a global safety factor (typically $\gamma \geq 2.0$ for foundations) against these ultimate limit states. Field reports from sites like the one in the province of Padova highlight that piles driven into clay-rich layers often exhibit higher skin friction compared to those in sandy layers, but they are also more susceptible to long-term creep under sustained tension [40], [41].

Alternative systems: concrete plinths and "root" micropiles

In soils with very poor mechanical properties (e.g., loose sands, peat, or soft clays) where friction piles would require excessive lengths to mobilize sufficient resistance, alternative solutions are employed. Concrete plinths involve casting a reinforced concrete block around the pile head or using precast ballasts. This solution relies on gravity; the mass of the concrete increases the resisting weight against uplift, while the enlarged footprint distributes compressive loads over a wider area to prevent settlement. Micropiles with radial anchors, such as the "TreeSystem" or similar screw-piles described in geotechnical manuals, mimic the root system of a tree. These systems utilize steel tubes equipped with varying geometries of helixes or insertable diagonal rods that lock into the soil at various angles. While these solutions offer high pull-out resistance in weak soils without the need for large volumes of concrete, they represent a niche solution due to significantly higher material costs and slower installation rates compared to standard ramming [17].

The steel-concrete interface and corrosion issues

When concrete foundations or backfills are used, or when piles are encased in plinths, the interaction between the hot-dip galvanized steel pile and the concrete creates a specific electrochemical environment that must be carefully managed. Fresh concrete is highly alkaline, with a pH typically between 12.5 and 13.5. As noted in steel metallurgy texts, zinc is an amphoteric metal; this means it corrodes in both highly acidic and highly alkaline environments. Upon initial contact with wet, fresh concrete, the outer zinc layer reacts to form calcium hydroxyzincate ($\text{Ca}[\text{Zn}(\text{OH})_3]_2 \cdot 2\text{H}_2\text{O}$). This reaction is accompanied by the evolution of hydrogen gas, which can locally increase the porosity of the concrete at the interface, potentially reducing the bond strength between the steel and the matrix. However, once the concrete cures and hardens, the pH stabilizes, and this layer effectively passivates the zinc, offering excellent long-term protection against corrosion as long as the concrete cover remains intact [18], [35].

A critical durability issue arises from poor detailing of the plinth geometry. In many installations, the concrete plinth is cast flush with the ground level or even slightly below grade to facilitate mowing. This creates a depression or a flat surface where rainwater and irrigation water can stagnate. This condition leads to the formation of a differential aeration cell at the steel-concrete-soil interface. The steel section immediately above the concrete is exposed to atmospheric oxygen (acting as the cathode), while the steel embedded in the wet, oxygen-deprived transition zone between the concrete and the soil acts as the anode. This localized electrochemical attack can lead to rapid dissolution of the zinc and subsequent pitting of the steel, potentially severing the pile at the base. To mitigate this risk, it is essential that the concrete plinth extends at least 10–15 cm above the finished grade. Furthermore, the top surface of the plinth must be chamfered or sloped (a "watershed" design) to ensure

rapid runoff of water, keeping the critical steel-concrete interface dry and preventing the accumulation of corrosive agents like fertilizer salts [15].

Mechanical damage during installation

The installation process itself introduces vulnerabilities that can compromise the long-term durability of the foundation. The impact energy delivered by the hydraulic hammer (often hundreds of joules per blow) causes significant mechanical stress on the pile head. Head deformation: the top of the pile often suffers plastic deformation, known as "mushrooming," where the steel profile buckles or flares out under the hammer blows. This deformation often distorts the pre-drilled bolt holes required for mounting the racking system. Consequently, installers are frequently forced to cut off the damaged section and drill new holes on-site. If these cut edges and new holes are not properly treated with a zinc-rich paint (cold galvanizing) according to ISO 1461 repair procedures, they leave the bare steel core exposed to the atmosphere, creating immediate initiation points for corrosion. Coating damage: as the pile penetrates the ground, abrasive friction with stones, gravel, and hard soil layers can strip the zinc coating, particularly at the corners and edges of the profile. This abrasion reduces the thickness of the protective layer, depleting the sacrificial reservoir available for underground protection. In the aggressive soil environments typical of agrivoltaics (characterized by fertilizers and humidity), this localized loss of coating can accelerate the onset of corrosion, reducing the effective service life of the foundation below the standard 25-30 year target [17].

3 Chapter 3: degradation mechanisms and corrosion theory

3.1. General corrosion mechanisms

3.1.1. Uniform corrosion and pitting

The degradation of metallic structures exposed to aggressive environments is primarily an electrochemical process. In order to properly design the foundation and the above-ground components of an agrivoltaic plant, it is necessary to understand the morphological distribution of the corrosive attack. The two fundamental categories of wet corrosion that affect these structures are uniform (or generalized) corrosion and localized corrosion, which includes pitting. The assumption of one mechanism over the other drastically changes the mathematical approach used to predict the service life of the components.

Uniform corrosion in homogeneous environments

Uniform corrosion is characterized by an electrochemical attack that proceeds evenly over the entire exposed surface of the metal. This occurs when the anodic and cathodic sites are microscopically small, continuously shifting, and statistically distributed across the entire metal surface [42]. Because the metal dissolves evenly, the structural degradation can be reliably quantified through average mass loss or average thickness reduction over time.

In homogeneous environments, such as the open atmosphere, the corrosion rate is primarily governed by the time of wetness and the deposition of pollutants, notably chlorides and sulphur dioxide. The standard ISO 9223 classifies the corrosivity of atmospheres into categories ranging from C1 (very low) to CX (extreme) [38]. In these atmospheric conditions, it is common engineering practice to assume the average coating thickness of a protective layer as a reliable reference point to calculate the structural decay. The expected useful life is mathematically derived by dividing the initial coating thickness by the specific annual corrosion rate associated with the environmental class.

To illustrate this concept, one can consider an atmospheric environment classified as C3 (medium corrosivity), which is typical for rural and low-pollution urban areas where many agrivoltaic plants are installed. According to the ISO 14713-1 standard,

the expected first-year corrosion rate for pure zinc in a C3 environment ranges from 0.7 to 2.1 μm per year [43]. If a structural profile is protected by traditional hot-dip galvanizing with a minimum mean coating thickness of 70 μm , the expected useful life before the underlying steel begins to corrode can be estimated conservatively by dividing 70 by the maximum rate of 2.1, resulting in approximately 33 years of protection.

When considering advanced zinc-aluminium-magnesium alloys in the same C3 atmospheric class, the degradation calculation changes. These alloys do not follow a purely linear degradation but rather an exponential negative behaviour over time due to the formation of highly stable, insoluble corrosion products like simonkolleite. Based on long-term predictive models, the corrosion evolution can be expressed by the power function where the corrosion at a given time is equal to the first-year corrosion rate multiplied by the time raised to a specific exponent usually less than one [29]. Because the initial corrosion rate is lower and the layer passivates over time, a zinc-magnesium coating of only 24 μm can provide a theoretical service life well exceeding 40 years in a C3 environment, outperforming much thicker traditional zinc coatings.

Weathering steel, or Corten, relies on a completely different homogeneous interaction with the atmosphere. In a C3 environment, the alternation of wet and dry cycles allows the alloying elements, primarily copper, chromium, and phosphorus, to foster the formation of a dense, adherent inner layer of amorphous oxyhydroxides [36]. Once this protective patina stabilizes after the first few years, the uniform corrosion rate of the steel drops to negligible values, often less than 10 μm per year. In such atmospheric conditions, Corten can easily guarantee the structural integrity of the plant for the entire design life of 30 years without any additional protective coating.

Uniform corrosion models applied to soil (category Im3)

While atmospheric models rely on the homogeneity of the air, underground applications introduce significant complexities. The standard ISO 12944-2 defines the category Im3 as the environment corresponding to buried structures [44]. Attempting to apply uniform corrosion calculations to soil requires careful consideration of the soil resistivity, pH, moisture content, and chemical composition.

If we evaluate the same three materials in an Im3 environment using generalized corrosion assumptions, the results differ drastically from the C3 atmospheric class. For standard hot-dip galvanized steel, geotechnical manuals indicate that in moderately aggressive soils, the uniform dissolution of zinc can reach 15 μm per year during the initial years, settling to around 4 μm per year subsequently [17]. A standard 85 μm coating might therefore endure for 15 to 20 years before the carbon steel substrate is exposed and begins to consume at a rate of 12 to 30 μm per year.

For zinc-aluminium-magnesium alloys, the application of uniform corrosion models in soil is still under study. While the self-healing properties remain active, the absolute

reservoir of the sacrificial coating is thin, usually 20 to 25 μm . In aggressive Im3 soils, a uniform dissolution model would predict a rapid depletion of this thin layer, leading to the conclusion that standard thin-gauge pre-galvanized profiles might not reach the 30-year design life underground without supplementary protection.

The case of weathering steel in the Im3 class perfectly illustrates the danger of improperly applying uniform corrosion concepts. In the soil, the continuous presence of moisture and the lack of proper aeration completely prevent the formation of the protective patina. Consequently, Corten behaves similarly like unalloyed carbon steel. Geotechnical corrosion studies demonstrate that unalloyed steel in soil can suffer uniform corrosion rates ranging from 0.05 to over 0.2 mm per year [19]. Over 30 years, this translates to a massive uniform thickness loss of 1.5 to 6.0 mm, which would inevitably lead to the structural collapse of a standard photovoltaic pile.

Pitting corrosion and the acceleration due to agrochemicals

The assumption of uniform corrosion becomes invalid when the passivity of the metal is broken locally, leading to pitting. Pitting is a highly localized form of corrosion where deep cavities or holes penetrate the metal at a rapid rate, while the surrounding surface remains largely unattacked. The mechanism is autocatalytic: the rapid dissolution of metal within the pit produces an excess of positive ions, which causes the migration of aggressive anions, most notably chlorides, into the cavity. The subsequent hydrolysis of metal chlorides generates hydrogen ions, dropping the pH inside the pit to highly acidic levels and further accelerating the dissolution rate [45].

In the specific context of agrivoltaics, the likelihood and severity of pitting are dramatically increased by the agricultural practices detailed in previous chapters. The intensive use of fertilizers introduces massive quantities of nitrates, sulphates, and chlorides into the soil electrolyte. Chlorides are notorious for their ability to penetrate protective oxide films and initiate pitting on galvanized steel, Corten and stainless steel components (such as bolts).

Furthermore, the application of phytosanitary products, particularly copper-based fungicides used in vineyards and organic farming, creates severe localized galvanic cells. When copper ions from these products wash into the soil and plate out as metallic copper onto the zinc surface of the piles, they act as highly efficient microscopic cathodes. This drives the rapid pitting of the surrounding anodic zinc. In these conditions, the corrosion rate cannot be evaluated using the average mass loss. The pitting factor, defined as the ratio between the deepest penetration and the average uniform corrosion depth, can range from 3 to 10 or more [18]. This means that if the uniform corrosion rate is calculated at 10 μm per year, a pit could be penetrating the steel at 100 μm per year, causing structural perforation and failure in a fraction of the predicted time.

Applicability of generalized corrosion to structural parts

Given the mechanisms described, it is necessary to rigorously distinguish where the assumption of generalized corrosion is actually applicable across the different parts of the agrivoltaic structure.

The above-ground superstructure, comprising the torque tubes, module rails, and the upper portions of the piles, is exposed to the atmosphere. In this region, assuming no localized accumulation of water or debris, the environment is homogeneous. Therefore, the uniform corrosion models based on ISO 9223 and the average coating thickness decay can be considered valid and reliable for predicting the service life of the components.

The transition zone, typically defined as the segment of the pile from 30 cm above the soil to 50 cm below the soil level, represents the most critical area. In this zone, the concept of generalized corrosion is inapplicable. The continuous fluctuation of moisture, the accumulation of fertilizer salts, and the presence of oxygen gradients create macroscopic differential aeration cells. The steel just below the soil line becomes anodic relative to the oxygen-rich steel above it, leading to severe localized dissolution [42]. Applying a uniform corrosion calculation here would grossly underestimate the structural risk.

For the deeply buried section of the pile, the applicability of uniform corrosion depends on the soil homogeneity. As described by the standard DIN 50929-3, if the soil is uniform in its resistivity and composition, the macroscopic galvanic currents are minimized, and the corrosion might proceed in a semi-uniform manner governed by the limited diffusion of oxygen [46]. However, soils are rarely perfectly homogeneous. The presence of different soil strata, clods of clay mixed with sand, or stray currents almost always induces localized anodic areas. Therefore, while uniform mass loss provides a baseline, a safety margin must always be applied to account for localised phenomena in the underground sections.

Finally, an interesting scenario arises if an element, such as a foundation pile, is completely and permanently immersed in stagnant water, without a transition zone exposed to the air. In this specific case, once the initial dissolved oxygen is consumed by the early corrosion reactions, the process becomes strictly limited by the slow diffusion of new oxygen through the water column. Because the water acts as a continuous and relatively homogeneous electrolyte, the formation of differential aeration cells is suppressed. Under these specific conditions, the corrosion tends to spread out and become genuinely generalized across the immersed surface [42]. The uniform corrosion rate in such deep water environments is often very low, provided that the water is not biologically active with sulphate-reducing bacteria and does not contain heavy concentrations of localized depassivating agents like high chlorides.

3.1.2. Galvanic corrosion: risk of bimetallic coupling

The structural integrity of an agrivoltaic plant relies on a complex assembly of different materials and components, each selected for specific mechanical or economic reasons. When two dissimilar metals are placed in direct electrical contact within a conductive electrolyte, such as humid air, rainwater, or moist soil, a galvanic cell is formed. The fundamental thermodynamic principle governing this phenomenon dictates that the metal with the more negative corrosion potential becomes the anode and undergoes accelerated dissolution, while the metal with the more positive potential acts as the cathode and receives protective reduction currents [42]. The severity of the resulting galvanic corrosion depends on the potential difference between the materials, the conductivity of the electrolyte, and critically, the surface area ratio between the cathode and the anode. In the context of agrivoltaics, these couplings can be classified into internal contacts among structural components, specific issues related to fasteners under stress, external contacts such as grounding grids, and macroscopic galvanic cells generated by soil heterogeneity.

Internal galvanic couplings within the structural framework

Agrivoltaic mounting systems are rarely monolithic. The necessity to optimize costs and mechanical performance often leads to hybrid material selections, which inevitably create bimetallic interfaces.

One of the most common interfaces occurs between the photovoltaic module frames, typically made of extruded anodized aluminium, and the supporting purlins, which are usually made of hot-dip galvanized steel or zinc-aluminium-magnesium alloys. Aluminium and zinc occupy relatively close positions in the galvanic series in neutral aqueous environments. Furthermore, the aluminium frames are protected by a thick, electrically insulating anodic oxide layer, which effectively breaks the galvanic circuit. However, in agricultural environments characterized by high humidity, the deposition of airborne fertilizers containing chlorides or the use of copper-based fungicides can degrade this passive film. If the anodic layer is breached, the zinc coating of the structure will act as an anode to protect the aluminium, leading to localized consumption of the galvanization at the clamping points [47].

Another increasingly common internal coupling occurs between different grades of zinc coatings. Secondary structural elements, such as purlins and brackets, are frequently manufactured from pre-galvanized coils using advanced zinc-aluminium-magnesium alloys, while the main driven piles are protected by traditional batch hot-dip galvanizing due to thickness requirements. Although both are zinc-based, the alloying elements in the zinc-aluminium-magnesium finish alter its electrochemical potential, generally making it slightly more anodic or altering its passivation kinetics compared to pure zinc. While the galvanic current between these two coatings is usually small, the continuous presence of agricultural moisture can lead to preferential

dissolution of the less noble phase at the bolted connections, requiring careful monitoring [32].

A far more critical internal coupling arises from the integration of weathering steel. Due to landscape integration constraints, designers sometimes propose hybrid structures where the above-ground superstructure is made of Corten steel to provide a visually pleasing brown patina, while the underground foundation pile is made of hot-dip galvanized steel, since Corten cannot develop its protective patina in the continuously wet and unaerated soil. Corten steel, being essentially a carbon steel alloyed with copper, chromium, and phosphorus, is significantly more noble than zinc. At the bolted or welded interface between the Corten superstructure and the galvanized pile, usually located near the ground level where moisture from dew, rain, and agricultural irrigation accumulates, a strong galvanic cell is established. The zinc coating will act as a sacrificial anode for the massive Corten cathode. Because the area of the Corten structure is large, the zinc coating at the connection point will be stripped away extremely rapidly, leaving the underlying carbon steel of the pile exposed to the aggressive environment [36]. To prevent catastrophic failure, these interfaces must be electrically isolated using dielectric gaskets and washers.

A similar macrocell phenomenon occurs between steel embedded in concrete foundations and adjacent galvanized steel structures. When a galvanized pile is cast into a concrete plinth, the portion of the steel embedded in the highly alkaline concrete (pH 12.5 to 13.5) becomes strongly passivated, assuming a noble potential. The portion of the galvanized pile exposed to the surrounding soil or damp atmosphere remains active. This creates a powerful macroscopic galvanic cell where the buried active zinc acts as an anode and corrodes rapidly to supply protective current to the massive, noble steel rebar cage embedded within the concrete. This interaction can drastically reduce the life of the galvanized pile at the concrete-soil [18].

The critical role of fasteners and mechanically stressed joints

The most vulnerable points of any metallic structure are the mechanical joints, primarily bolts, nuts, and washers. The risk here is governed by the area effect principle. In a galvanic couple, the corrosion current density on the anode is determined by the ratio of the cathodic area to the anodic area.

A common design error is the use of galvanized steel bolts to connect Corten steel profiles. In this scenario, the highly noble Corten acts as an enormous cathode, while the zinc coating on the small bolt acts as the anode. The extremely large cathode-to-anode area ratio forces a massive corrosion current through the small surface of the bolt, leading to the rapid dissolution of the zinc coating and the subsequent severe corrosion of the bolt's steel core, compromising the structural safety of the entire tracker or fixed-tilt table [48].

Conversely, the use of stainless steel bolts on a hot-dip galvanized structure represents a favourable area ratio. The stainless steel bolt acts as the noble cathode, and the massive galvanized structure acts as the anode. Because the anodic area is vastly larger than the cathodic area, the corrosion current is distributed over a wide surface, resulting in a negligible increase in the uniform corrosion rate of the galvanized pile.

However, fasteners are not only subject to electrochemical dissolution; they are also subjected to high mechanical tensile stresses, which introduces the risk of environmentally induced cracking. When a high-strength steel bolt is galvanically coupled to a more noble material in an acidic environment, or when agricultural chemicals locally depress the pH, the anodic reaction of the zinc is accompanied by the cathodic evolution of hydrogen. Atomic hydrogen can absorb into the highly stressed crystal lattice of the bolt. In high-strength steels, this leads to hydrogen embrittlement, a sudden and catastrophic brittle failure of the fastener without prior plastic deformation. Alternatively, if the environment contains specific aggressive ions such as chlorides from fertilizers or sulfur compounds, the stressed fasteners can suffer from stress corrosion cracking, where microscopic cracks propagate rapidly through the metal grains under the combined action of tension and localized corrosion. [45].

External galvanic couplings: the grounding grid

For electrical safety and lightning protection, agrivoltaic plants require an extensive underground grounding grid. Traditionally, these grids are constructed using bare copper cables and rods due to copper's excellent electrical conductivity and intrinsic resistance to soil corrosion. However, copper is one of the most noble engineering metals.

When the galvanized steel structural piles are electrically bonded to the bare copper grounding grid to ensure equipotentiality, a massive galvanic macrocell is inadvertently created in the soil. The entire network of galvanized piles acts as an anode, sacrificing its zinc coating to protect the highly noble copper grid. The high electrical conductivity of the copper network facilitates the collection of cathodic currents from a vast area of soil, focusing the anodic dissolution onto the nearest galvanized piles. Studies have shown that in such bimetallic configurations, the corrosion rate of the galvanized steel can be accelerated by several orders of magnitude, stripping the protective zinc layer in a matter of months rather than decades [49]. To mitigate this severe risk, modern engineering practices suggest using heavily galvanized steel for the grounding grid itself, or using insulated copper cables that only expose bare copper at specific deep grounding rods far from the structural piles.

Soil heterogeneity and differential aeration macrocells

Even in the absence of dissimilar metals, severe galvanic corrosion can occur on a single, uniform steel pile due to the physical and chemical heterogeneity of the soil

environment. The soil is not a uniform electrolyte; its properties change dramatically with depth, moisture content, compaction, and agricultural chemical loading. These variations create concentration cells on the surface of the buried pile.

The most aggressive of these is the differential aeration cell. Oxygen from the atmosphere diffuses easily into the superficial, porous layers of the soil, but its concentration drops rapidly with depth, especially in waterlogged or clay-rich strata. On a vertical pile driven into the ground, the steel surface located in the oxygen-rich superficial zone becomes the cathode, while the deeply buried steel in the oxygen-depleted zone becomes the anode. A galvanic current flows through the soil from the deep anodic areas to the shallow cathodic areas, resulting in severe localized dissolution of the metal at depth [42].

This phenomenon is exacerbated by agricultural practices. The topsoil is frequently wetted by irrigation and subsequently dried, creating cyclic changes in electrolyte resistance. Furthermore, the superficial application of fertilizers creates a gradient of dissolved salts. The standard DIN 50929-3 provides a rigorous framework for evaluating these complex soil interactions. It classifies the probability of corrosion based on a multifactorial index that accounts for soil resistivity, moisture, pH, and the concentration of specific aggressive ions like sulphates and chlorides [46].

According to the interpretation of DIN 50929-3, zinc coatings are highly susceptible to variations in soil resistivity and the presence of external cathodes. In soils with high concentrations of chlorides and sulphates from fertilizers, the local resistivity drops, facilitating large galvanic currents. The presence of sulphate-reducing bacteria in anaerobic, deep soil layers can further depolarize the anodic reaction, destroying the zinc. If Corten steel is buried, the standard indicates that the lack of aeration and the presence of soil moisture prevent the formation of the protective oxyhydroxide patina, causing the material to behave similarly to ordinary carbon steel, subject to macrocell attack driven by the differential aeration. Finally, the standard also addresses the degradation of concrete foundations in soil. High concentrations of sulphates in agricultural soils can react with the tricalcium aluminate in the cement matrix, causing expansive ettringite formation that cracks the concrete cover. Once the concrete is cracked, the highly alkaline environment is neutralized by groundwater, depassivating the internal steel rebars and initiating a galvanic cell between the active steel in the cracks and the passive steel in the intact concrete, leading to structural spalling.

3.1.3. Stray current corrosion from external DC sources

The phenomenon of stray current corrosion occurs when electrical currents flow through paths other than their intended circuits, utilizing the earth and buried metallic structures as conductive mediums. In the context of agrivoltaic plants, which are inherently massive electrical generation facilities, it is a common preliminary

assumption to associate the risk of stray current corrosion with the direct current generated by the photovoltaic modules themselves. However, a rigorous technical analysis of modern plant design largely dismisses this internal risk, shifting the engineering focus towards external infrastructural interferences.

When evaluating the risk of internal direct current leakage, it is essential to understand the electrical topology of a modern photovoltaic array. The strings of solar panels and the direct current wiring connecting them to the inverters operate as an isolated system (IT grounding system) under normal conditions. The direct current does not use the earth as a return path. While a mechanical degradation of the cable sheathing, perhaps caused by rodent bites, agricultural machinery, or friction against a sharp galvanized steel purlin, could theoretically cause a direct current leakage into the metallic mounting structure and subsequently into the soil, this does not result in chronic stray current corrosion. Modern inverters and string combiner boxes are equipped with continuous insulation monitoring devices. As dictated by electrical safety standards, the moment these devices detect a drop in insulation resistance or a ground fault, they immediately interrupt the circuit and shut down the affected section of the plant. Consequently, any corrosion induced by the plant's own electricity represents an acute, transient fault condition rather than a continuous degradation mechanism that must be factored into the structural design life. The time of exposure to the leakage current is practically negligible before the system trips.

The genuine and significant risk of stray current corrosion, often referred to as interference corrosion, originates from massive external electrical direct current sources. The most prominent and aggressive example in the context of agrivoltaic installations is the proximity to electrified railway networks [18]. In many European countries, including Italy, regional and high-speed train networks frequently operate on direct current traction systems (commonly 3 kV). In these systems, the overhead catenary line acts as the power supply, while the running steel rails serve as the return conductor back to the electrical substation. Because the rails are in physical contact with the ground through the ballast and are never perfectly electrically insulated from the earth, a portion of the high-amperage return current inevitably leaks into the subsoil.

Urban and agricultural planning regulations often permit the construction of ground-mounted photovoltaic and agrivoltaic plants at a relatively short safety distance from railway infrastructures, frequently maintaining a buffer of just 30 m from the tracks. This spatial proximity places the extensive network of deep metallic foundations of the solar trackers directly within the potential underground path of these erratic traction currents.

The severity of the resulting interference is dictated by the fundamental principles of electrical resistance and the laws of electrochemistry. When stray currents flow through the ground, they invariably seek the path of least resistance. The steel piles of

an agrivoltaic plant, driven several meters into the earth, offer a highly conductive metallic route compared to the surrounding soil. The direct current enters the metallic pile at a specific underground location closest to the high-potential area of the rail, travels virtually without resistance along the steel profile, and then must exit the pile at another location closer to the railway substation to resume its path through the soil towards its source.

As detailed in corrosion science literature, the localized areas where the current enters and exits the metallic structure behave completely differently. The point where the positive current enters the structure acts as a cathode. At this location, the metal is completely protected from corrosion; the electrochemical reactions are dominated by the reduction of oxygen or the evolution of hydrogen, which locally increases the alkalinity of the soil but does not dissolve the steel. Conversely, the exact point where the direct current leaves the metal and re-enters the soil electrolyte acts as an extremely powerful forced anode [42]. At this exit point, the anodic dissolution of the metal is forcefully accelerated by the external electromotive force. According to Faraday's law of electrolysis, the mass of metal dissolved is strictly proportional to the electrical charge that passes through the interface. For carbon steel and zinc, the discharge of just one ampere of continuous direct current into the soil can consume nearly nine kilograms of metal in a single year, a degradation rate that dwarfs any natural environmental corrosion process.

The radius of influence of a railway line and the subsequent magnitude of the current captured by the agrivoltaic piles are heavily influenced by the geotechnical properties of the specific site. Soil resistivity is the governing parameter. In pure, dry, sandy soils, the high electrical resistance limits the spread of stray currents, making the 30 m safety distance generally sufficient to prevent significant interference. However, the agrivoltaic environment is unique. The agricultural vocation of the land requires constant moisture maintenance through irrigation and the frequent application of fertilizers. The dissolution of nitrates, sulphates, and chlorides from these agricultural inputs creates a highly concentrated electrolyte in the soil pore water [49]. This agronomic activity drastically lowers the electrical resistivity of the soil, often dropping it below $20 \Omega \cdot \text{m}$. This highly conductive medium facilitates the propagation of stray currents over much longer distances, effectively nullifying the protection supposedly offered by the standard 30 m buffer zone. The current easily bridges the gap between the leaking rail and the conductive foundation of the solar tracker.

If an agrivoltaic pile were subjected to continuous stray current interference from a nearby railway, the resulting structural damage would be insidious and highly localized. Because the current exit point, the anodic zone where dissolution occurs, is dictated by the path of least electrical resistance back to the substation, the damage almost never occurs at the soil surface. Instead, the current typically exits the pile deep underground, often at the level of the water table or where the pile intersects a

particularly conductive stratum of wet clay. Because of this, visual inspections of the above-ground structure or the shallow transition zone will reveal absolutely no signs of distress. The structure will appear perfectly healthy while being critically undermined below ground.

During a direct extraction of an affected pile (e.g. in case of revamping or dismantling), the unique morphology of stray current corrosion becomes immediately apparent. Unlike the uniform rust or broad shallow pitting typical of natural soil corrosion, stray current damage presents as deep, steep-sided craters or macroscopic holes cleanly bored into the steel profile [18]. The intense localized electrical field strips away the zinc coating almost instantly and rapidly drills through the underlying carbon steel base. In severe cases, the structural cross-section of the pile can be completely severed in a matter of couple years, leading to the sudden collapse of the tracker under wind loading.

Despite the extreme theoretical severity of this electrochemical mechanism, stray current corrosion is, as of today, not a widely reported or structurally debilitating problem across the general fleet of agrivoltaic plants. There are several engineering and circumstantial reasons for this current reality. Firstly, the heavy hot-dip galvanization applied to the structural piles, coupled with the polarization resistance of the soil-metal interface, provides a certain threshold barrier that low-voltage stray currents struggle to overcome. Secondly, the architectural layout of utility-scale plants involves thousands of piles electrically bonded together through the superstructure and the equipotential grounding grid. This vast interconnected network acts as an enormous grounding mat, which tends to disperse and dilute the density of the exiting currents over a massive surface area, reducing the localized dissolution rate to levels that often blend in with natural soil corrosion allowances [50].

Most importantly, for severe and rapid stray current failure to occur, a highly specific convergence of worst-case parameters is required: the plant must be built extremely close to a heavily trafficked direct current railway, the specific alignment of the tracker rows must offer a parallel low-resistance shortcut for the rail return current, and the soil must be highly conductive and waterlogged at depth. Because this exact combination of factors is statistically rare, the phenomenon remains isolated to highly specific sub-sections of specific plants. Consequently, while the evaluation of railway interference remains a mandatory aspect of the preliminary site screening and geotechnical survey phase, it currently does not necessitate a systemic change in the baseline foundation design or the widespread adoption of active cathodic protection systems across the agrivoltaic sector.

3.2. Soil corrosion physics

3.2.1. The role of resistivity, pH, water content and redox potential

The degradation of metallic structures buried in the ground represents one of the most complex phenomena in corrosion science. Unlike atmospheric environments, which can be treated as relatively homogeneous and predictable over large areas, the soil is a highly heterogeneous, multiphase system composed of solid mineral particles, organic matter, aqueous solutions, and interconnected gaseous voids [47]. For agrivoltaic structures, the foundation piles are driven directly into this dynamic environment. It is a fundamental engineering premise that weathering steel, commonly known as Corten, cannot develop its protective oxyhydroxide patina when buried because it lacks the necessary alternating wet and dry cycles and sufficient aeration. Consequently, in underground applications, Corten behaves proportionally to standard unalloyed carbon steel, suffering from continuous and often accelerated degradation [36]. Hot-dip galvanized steel, on the other hand, relies on the sacrificial and barrier properties of its zinc coating, which is highly sensitive to the specific chemical composition of the soil pore water. To properly design the foundations, it is essential to understand the physical and chemical parameters that govern soil corrosivity and how they are codified in international engineering standards.

Regulatory frameworks: a comparison between ISO 12501 and DIN 50929-3

The assessment of soil corrosivity has historically been approached through various empirical and semi-empirical methods. Currently, two primary European standards provide guidelines for evaluating the corrosion load on buried metallic structures: the ISO 12501 series and the DIN 50929-3 standard.

The standard ISO 12501-2 provides a basic, qualitative methodology for estimating the likelihood of corrosion in soils for low-alloyed and unalloyed ferrous materials [51]. This standard adopts a highly simplified approach, primarily taking into account only two variables: the pH value of the soil and its electrical resistivity. Based on the intersection of these two parameters, the standard classifies the corrosion load into three broad categories: low, medium, and high. While this method is easy to apply during preliminary desktop studies, its fundamental limitation lies in its univariate and bivariate nature. It completely ignores the synergistic effects of localized ion concentrations, soil heterogeneity, and biological activity, which are precisely the factors that drive the most severe corrosion failures in agricultural settings.

In stark contrast, the German standard DIN 50929-3 offers a comprehensive, multifactorial framework that is widely considered the state of the art for geotechnical corrosion engineering. This standard calculates the probability of free corrosion by assigning rating numbers, designated as Z factors, to a wide array of measurable soil properties [46]. These ratings are algebraic values that can be positive (indicating a

protective or benign effect) or negative (indicating an aggressive or corrosive effect). The individual ratings are summed to produce a total rating number, denoted as B_0 , which represents the corrosion load of the homogeneous soil.

The evaluation includes parameters such as the type of soil and its cohesion (Z_1), specific electrical soil resistivity (Z_2), moisture content (Z_3), pH value (Z_4), and acid capacity or buffering capacity (Z_5). Crucially, the standard also heavily penalizes the presence of specific aggressive agents, assigning negative ratings for sulfides (Z_6), neutral salts like chlorides (Z_7), and sulfates (Z_8). The standard goes beyond the homogeneous chemical composition by evaluating the physical placement of the structure, incorporating factors for the location with respect to groundwater (Z_{10}) and horizontal or vertical soil heterogeneity (Z_{11} , Z_{12} , Z_{13}), which are the primary causes of macroscopic galvanic cells. Finally, it accounts for the presence of external cathodes (Z_{15}). Based on the final sum B_0 ,

$$B_0 = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 + Z_7 + Z_8 + Z_9 + Z_{10}$$

the soil is classified into categories ranging from practically non-corrosive to highly corrosive, providing specific expected rates for both uniform corrosion and localized pitting corrosion [46]. This detailed approach is far more suitable for agrivoltaic systems, where the soil is artificially modified by farming practices.

Intrinsic elements of soil composition and their weight

The aggressiveness of a soil towards carbon steel (including Corten) and galvanized steel is determined by the complex iteration of several intrinsic elements. Evaluating their individual weight helps in understanding the overall corrosion mechanism.

Electrical resistivity is universally recognized as the most critical and heavily weighted parameter in assessing soil corrosivity. Resistivity, measured in $\Omega \cdot m$, dictates the ability of the soil to conduct the ionic currents associated with galvanic corrosion cells. A high resistivity implies that the flow of corrosion current between anodic and cathodic areas is impeded, severely limiting the corrosion rate. Conversely, a low resistivity facilitates rapid charge transfer, accelerating metal dissolution. According to geotechnical classifications and the DIN 50929-3 standard, soils with a resistivity greater than $100 \Omega \cdot m$ are generally considered mildly corrosive, while values dropping below $20 \Omega \cdot m$, and especially below $10 \Omega \cdot m$, indicate a highly corrosive environment [17]. In the context of agrivoltaics, resistivity is not a static geological trait. The application of chemical fertilizers introduces massive quantities of soluble salts, such as nitrates, chlorides, and potassium, into the soil matrix. These ions act as charge carriers, drastically depressing the electrical resistivity of the agricultural land compared to its natural state, thereby increasing the weight of this aggressive factor.

The pH value of the soil water extract plays a fundamental role in determining the thermodynamic stability of the metallic elements and their corrosion products. For carbon steel and Corten, the corrosion rate is relatively independent of pH within the

neutral to slightly alkaline range (pH 6 to 8) because a semi-protective layer of iron oxides can precipitate. However, when the pH drops below 5, the environment becomes highly acidic, the protective oxides dissolve, and the corrosion rate increases exponentially, driven by the cathodic evolution of hydrogen gas [49]. Zinc, which constitutes the protective coating of galvanized piles, is an amphoteric metal. This means it suffers severe corrosion in both acidic environments and highly alkaline environments. It exhibits its minimum corrosion rate in a narrow pH window between roughly 7 and 12, where it forms a passive layer of zinc hydroxide and zinc carbonate. Agricultural soils are frequently subjected to artificial acidification. The prolonged use of ammonium-based fertilizers and the decomposition of organic matter generate hydrogen ions, locally lowering the pH around the pile and stripping away the protective zinc layer much faster than anticipated by standard atmospheric models.

Soil moisture and water content represent the absolute prerequisite for underground electrochemical corrosion. Without water, there is no electrolyte, and corrosion cannot occur. Moisture in the soil acts as the conductive medium that connects the anodic and cathodic sites on the metal surface. The relationship between moisture content and corrosion is direct but not entirely linear. Up to a certain saturation point, an increase in water content continuously lowers the soil resistivity and increases the corrosion rate by providing a more continuous electrolytic path. However, when the soil reaches full water saturation, all the pore spaces are filled with water, which severely restricts the diffusion of oxygen from the atmosphere. Since oxygen reduction is the primary cathodic reaction in neutral soils, waterlogged conditions can eventually stifle the corrosion rate of unalloyed steel due to cathodic polarization [42].

The redox potential, or oxidation-reduction potential, is a measure of the degree of aeration of the soil. It is heavily weighted when predicting the risk of microbiologically influenced corrosion. A high, positive redox potential indicates a well-aerated soil where oxygen is plentiful. A low or negative redox potential indicates an anoxic, reducing environment, typical of dense, waterlogged clays or stagnant muds. While a lack of oxygen slows down standard electrochemical corrosion, a severely negative redox potential creates the ideal breeding ground for obligate anaerobic bacteria, such as sulfate-reducing bacteria. These microorganisms depolarize the cathodic reaction by consuming hydrogen and reduce naturally occurring sulfates into highly aggressive hydrogen sulfide, causing severe pitting on both steel and zinc in environments that would otherwise be considered benign [19].

Spatiotemporal variations and the influence of agricultural agents

The parameters described above are not constant; they exhibit profound variations over time, with depth, and in response to external agricultural manipulation.

Regarding spatial variation with depth, a driven agrivoltaic pile crosses several distinct soil horizons. The superficial topsoil, typically the first 30-50 cm, is highly

aerated due to its proximity to the atmosphere and its loose structure caused by plowing and root growth. This layer is also the most heavily laden with chemical fertilizers and organic matter. Beneath this lies the subsoil, which is generally more compacted, retains moisture for longer periods, and has a significantly lower oxygen concentration. This vertical stratification creates a powerful differential aeration macrocell along the length of the steel pile. The well-aerated steel surface in the topsoil assumes a noble potential and acts as a cathode, while the oxygen-deprived steel in the deeper, constantly moist subsoil acts as an anode. The resulting galvanic current flows through the conductive soil, causing accelerated, localized dissolution of the metal at depth, specifically at the interface between the aerated and non-aerated zones [42].

In addition to depth, soil composition dictates the physical retention of these aggressive factors. Sandy and gravelly soils possess high porosity and hydraulic conductivity. They drain water rapidly and allow oxygen to permeate deeply, generally resulting in higher resistivity and more uniform, albeit lower, corrosion rates. Conversely, clay soils are composed of ultrafine particles that trap water and soluble salts tightly. They exhibit low resistivity, poor drainage, and poor aeration. The localized variations in clay clods pressing against the steel surface often lead to severe pitting, as the areas under the compacted clay become anodic relative to adjacent areas exposed to small pockets of trapped air [49].

Temporally, the corrosivity of the agrivoltaic soil fluctuates with the seasons and agricultural cycles. During dry summer months, the soil moisture drops, resistivity increases, and the corrosion process slows down or halts entirely. The subsequent application of irrigation or the arrival of autumn rains rapidly saturates the soil. This sudden influx of water dissolves the accumulated fertilizer salts that were deposited during the dry period, creating a highly concentrated, highly conductive electrolyte spike that triggers a sudden burst of corrosive activity. These wet and dry cycles ensure that the corrosion process is continually reactivated, preventing the long-term stabilization of any naturally formed protective corrosion products on the steel surface.

Empirical evidence and practical cases of underground corrosion

The theoretical frameworks of soil corrosion find robust validation in extensive field investigations. The most prominent and foundational practical case is the monumental study conducted by Melvin Romanoff for the United States National Bureau of Standards, documented in Circular 579. Over a period of several decades, the bureau buried thousands of specimens of unalloyed steel, cast iron, and galvanized steel in a wide variety of soils across the country.

Romanoff's data clearly demonstrated that the corrosion of ferrous metals in soils is overwhelmingly characterized by localized pitting rather than uniform dissolution. In

well-drained soils with high resistivity, the corrosion was found to be high initially but decreased substantially after a few years to almost complete cessation of pitting, due to the formation of adherent rust layers. Conversely, in poorly drained soils having low resistivities, such as heavy clays and mucks, the rate of corrosion was nearly constant with time, leading to deep and destructive penetration. Romanoff also highlighted the devastating impact of specific chemical compositions; soils containing cinders, which release sulfuric acid and act as massive external cathodes, or soils with extreme acidity, caused the most rapid destruction of the specimens. Regarding galvanized steel, Romanoff found that a heavy zinc coating provided excellent protection in most inorganic soils, delaying the onset of steel pitting by decades. However, in highly acidic soils or those with very high concentrations of sulfates and chlorides, the zinc coating was rapidly consumed, offering only a brief extension of the structure's lifespan [19].

More recent practical cases further correlate soil analysis to corrosion in specific agricultural and modern contexts. Studies investigating the failure of galvanized steel pipes in water irrigation systems, such as central pivots used in fertigation, have shown that the direct application of liquid fertilizers continuously renews the aggressive ions at the metal-soil interface. Research by Wu et al. on X80 steel and Q235 steel in simulated soil solutions demonstrated a direct relationship between the decreasing pH value and the weight loss of the steel, alongside an increase in the cathodic corrosion current density [49]. Furthermore, investigations into the corrosion behaviour of metals in saline soils and coastal agricultural lands emphasize that the presence of chloride ions not only decreases resistivity but specifically attacks the passive films formed on zinc and aluminium alloys, initiating autocatalytic pitting cells that rapidly penetrate the structural thickness. These practical cases underscore the necessity of moving beyond simplified standards like ISO 12501 and adopting the rigorous, site-specific, and multifactorial approach dictated by DIN 50929-3 when designing the deep foundations of agrivoltaic plants.

3.2.2. The differential aeration cell at the air/soil transition zone

The durability of driven steel piles in agrivoltaic systems is intrinsically tied to the availability and distribution of oxygen within the soil matrix. While uniform corrosion models assume a homogeneous distribution of reactants, the reality of the underground environment is characterized by severe chemical and physical gradients. The most destructive of these gradients is the variation in oxygen concentration, which gives rise to the differential aeration cell, also known as the Evans cell. According to fundamental electrochemistry, when a single metallic structure is exposed to an electrolyte with varying concentrations of dissolved oxygen, the areas of the metal in contact with the higher oxygen concentration assume a more noble electrochemical potential and act as cathodes, while the areas in contact with the lower oxygen

concentration assume a more active potential and become forced anodes [42]. In the context of an agrivoltaic foundation pile, which spans from the open atmosphere down to depths of several meters into the earth, this phenomenon dictates the exact location and severity of structural degradation.

Oxygen and carbon dioxide concentration gradients with depth

To fully comprehend the mechanics of the differential aeration cell along a standard agrivoltaic pile, it is necessary to model the variation of the gaseous composition of the soil at microscopic intervals. The diffusion of gases in the soil is governed by Fick's laws, the total porosity of the medium, and the degree of water saturation. As highlighted in geotechnical corrosion studies, the water content determines the subsequent diffusion of oxygen; a higher water content corresponds to a lower air fraction due to the decreasing free volume between soil particles [21].

If we analyze a typical agricultural soil profile from the surface down to a depth of 4 m, proceeding in theoretical intervals of 0.1 m, we observe an inverse asymptotic relationship between oxygen and carbon dioxide. At the immediate surface boundary, from 0.0 to 0.1 m, the soil is in direct communication with the atmosphere. Here, the oxygen concentration is virtually identical to that of the air, approximately 20.9 % by volume, while carbon dioxide is near the atmospheric baseline of 0.04 %.

As we descend through the telluric layer, from 0.1 to 0.5 m, the soil is typically subjected to agricultural tilling, which maintains a high macroscopic porosity. However, this is also the zone of maximum biological activity. Plant roots, aerobic bacteria, and fungi continuously consume oxygen for respiration and release carbon dioxide. Consequently, in this first half-meter, measured at every decimeter, the oxygen concentration begins to drop gradually from 20 % down to approximately 15 to 18 %. Carbon dioxide levels can spike to 1 or 2 %, accumulating in the pore spaces due to its higher molecular weight compared to standard air.

Proceeding deeper, from 0.5 m to 1.5 m, the soil compaction naturally increases, and the influence of mechanical plowing ceases. The macro-pores become less frequent, and the capillary retention of moisture increases. In this stratum, the oxygen concentration gradient becomes much steeper. Literature describes a strictly decreasing oxygen content in the soil downwards, which, according to the Nernst equation, generates significant potential differences, making the upper regions progressively more noble [21]. For every 0.1 m descended, the oxygen level may drop by a full percentage point or more, as the physical barrier of compacted soil and capillary water severely restricts the downward diffusion of atmospheric oxygen. By the time the 1.5 m depth is reached, the oxygen concentration may be reduced to 5 to 10 %. Concurrently, the carbon dioxide produced by deeper root systems and anaerobic decomposition finds it difficult to escape upwards; its concentration can rise

to 5 % or more, dissolving into the soil moisture to form weak carbonic acid, thereby locally lowering the pH.

From 1.5 m down to 2.5 m, the pile often enters the capillary fringe, the zone immediately above the groundwater table where soil pores are almost entirely filled with water drawn up by capillary action. Because the diffusion coefficient of oxygen in water is approximately 10000 times lower than its diffusion coefficient in air [42], this zone acts as a massive barrier. Analyzing this section decimeter by decimeter reveals a drastic plunge in available oxygen, dropping rapidly from 5 % to less than 1 %. Furthermore, as confirmed by infrastructure monitoring programs, dissolved oxygen concentrations within water typically decrease exponentially with water depth [53].

Finally, from 2.5 m down to the pile tip at 4.0 m, the foundation is typically fully immersed in the saturated zone or water table. In this deep region, the environment is fundamentally anoxic, a condition well documented in studies concerning the anoxic corrosion behavior of pipeline steels in acidic and neutral soils [51]. The oxygen concentration is virtually zero, limited only to trace amounts of dissolved oxygen carried by groundwater flow. The carbon dioxide concentration here reaches its maximum equilibrium with the water, creating a completely reducing environment. This profound difference between the highly oxygenated top 0.5 m and the completely anoxic environment at 4.0 m is the fundamental thermodynamic engine that drives the differential aeration macrocell along the steel profile [19].

Seasonal variations, water table fluctuations, and operating conditions

The gaseous profile described above is not static; it is highly dynamic and fiercely dependent on seasonal weather patterns, irrigation practices, and the subsequent fluctuation of the water table. The water content in the soil is the primary modulator of permeability and, consequently, of the aeration gradient.

Under ordinary operating conditions during the dry summer months, agricultural soils lose moisture through evaporation and plant transpiration. As the water vacates the capillary pores, air is drawn deeper into the ground. The transition zone where oxygen drops to near-zero is pushed significantly lower, perhaps moving from 2.0 m down to 3.0 m. During this phase, the overall resistance of the soil electrolyte increases due to the lack of moisture, which generally slows down the global rate of the galvanic currents.

Conversely, during the wet autumn and winter seasons, or following intense agricultural irrigation, the soil profile becomes rapidly saturated from the top down. The rainwater fills the voids, forcefully expelling the soil air. The oxygen concentration in the top 1.0 m plummets. More importantly, the water table rises. This seasonal rising and falling of the water table means that the boundary between the aerated cathode and the anoxic anode is constantly shifting up and down the pile.

In extreme conditions, such as prolonged flooding or waterlogging typical of poorly drained clay basins, the entire soil profile from 0.0 to 4.0 m becomes saturated. The differential aeration cell is temporarily suppressed because the entire underground pile is deprived of oxygen. While electrochemical corrosion slows down in these extreme anoxic conditions, the highly reducing environment combined with the presence of organic agricultural matter creates the perfect conditions for microbiologically influenced corrosion. This allows anaerobic species, such as sulfate-reducing bacteria, to attack the deep sections of the pile [47]. On the opposite extreme, during severe droughts, the complete absence of an aqueous electrolyte breaks the galvanic circuit entirely, temporarily halting the corrosion process until the next rainfall.

Stratigraphy and the formation of multiple underground macrocells

While the overall depth gradient creates a primary macrocell between the topsoil and the deep subsoil, the specific geological stratigraphy of the site creates numerous, highly localized secondary differential aeration cells. The subsoil is rarely a homogeneous column; it is built of alternating layers of different materials, each with its own intrinsic permeability and water retention capacity.

If an agrivoltaic pile is driven through a sequence of strata, for example, a highly permeable sandy layer at 1.0 m, followed by a dense, impermeable clay layer at 2.0 m, and another sandy gravel layer at 3.0 m, a complex series of galvanic cells is established. The sandy layers have large pore spaces that drain water easily and allow oxygen to permeate laterally. The steel surfaces in contact with these sandy strata become well-aerated cathodes.

The clay layer, composed of ultrafine particles, traps water tightly and completely blocks the diffusion of oxygen. The steel surface crossing this 2.0 m clay layer becomes severely oxygen-starved and acts as the anode. A powerful galvanic current will flow from the anodic steel in the clay, through the soil electrolyte, to the cathodic steel in the adjacent sand layers. This results in severe, localized lateral corrosion exactly at the boundaries where the soil type changes [17]. The attack will not be uniform; instead, deep macroscopic pits or large craters will form specifically on the portion of the pile embedded in the clay, right at the interface with the sand. This implies that the variation in permeability due to stratigraphy can be just as dangerous as the general depth gradient.

The air/soil transition zone: quantification of the localized attack

Of all the differential aeration cells formed across the structure, none is more aggressive or structurally threatening than the primary cell established at the exact ground level, commonly referred to as the air/soil transition zone or the splash zone.

At this precise interface, typically extending from 0.1 m above the soil to 0.3 m below the soil, the conditions for maximum corrosion are perfectly aligned. The steel

immediately above the ground is fully exposed to atmospheric oxygen, providing an infinitely renewable, highly efficient cathode. The steel immediately below the soil line is wetted by soil moisture, which is highly conductive due to the presence of dissolved agricultural fertilizers, yet it is slightly shielded from the air by the thin layer of topsoil, making it the anode [18].

Because the cathodic area above ground is massive, comprising the entire superstructure of the solar tracker, and the anodic area below ground is restricted to a narrow band of constantly wet steel, the cathode-to-anode area ratio is extremely high. According to the principles of galvanic corrosion, this high ratio concentrates the entirety of the corrosion current onto a very small area of sacrificial metal.

In numerical terms of proportionality, while the deep underground sections of the pile might suffer a uniform thickness loss of 10 to 20 μm per year, the intense localized attack at the transition zone can reach penetration rates of 100 to 300 μm per year. The pitting factor, which is the ratio of the deepest localized penetration to the average uniform corrosion, frequently exceeds a value of 10 in this specific band [19].

The type of attack that verifies in this zone is rarely a wide, even dissolution. Instead, it presents as severe necking or ring-off corrosion. The zinc coating is stripped away in a matter of a few years, and the underlying carbon steel is eaten away in a concentrated horizontal band around the perimeter of the profile. This specific morphology is exceptionally dangerous because it occurs exactly at the point of maximum bending moment for the pile, which acts as a cantilever fixed in the ground. The wind loads acting on the photovoltaic panels generate the highest stress precisely at the soil line. Therefore, a localized reduction of the cross-sectional area of even 20 % at this specific transition bottleneck can drastically reduce the moment of inertia of the profile, leading to the sudden yielding and collapse of the entire structure during a severe storm, long before the rest of the underground pile shows any significant signs of degradation.

3.3. Specific effects of fertilizers

3.3.1. Chemical kinetics of zinc with nitrates and sulfates

The integration of photovoltaic structures within active agricultural land fundamentally alters the conventional assumptions of soil corrosivity. While standard geotechnical engineering evaluates undisturbed soils, agrivoltaic foundations are immersed in a dynamic, artificially modified biochemical reactor. The continuous introduction of agrochemicals, specifically fertilizers, radically shifts the electrolyte composition, the pH, and the electrical resistivity of the soil pore water. To guarantee the structural integrity and the expected service life of the plant, it is mandatory to deeply understand the typologies of applied fertilizers, their distribution

methodologies, and the specific chemical attack kinetics they trigger on hot-dip galvanized steel, weathering steel, and concrete foundations.

Typologies of fertilizers, target crops, and application methods

Agricultural fertilization is designed to replenish the macroscopic nutrients essential for plant growth, primarily nitrogen, phosphorus, and potassium. In the context of the severe corrosion phenomena observed in agrivoltaic plants, nitrogenous and sulfatic fertilizers play the most detrimental roles.

Nitrogen-based fertilizers are the most universally applied agrochemicals across almost all intensive farming models. The most common commercial forms include urea, ammonium nitrate, and ammonium sulfate. These compounds are heavily utilized in the cultivation of extensive cereal crops such as wheat, corn, and barley, which require massive nitrogen inputs to sustain rapid vegetative growth and high grain yields. Sulfatic fertilizers, such as potassium sulfate or superphosphates, are frequently applied to specialized crops, including vineyards, orchards, and specific vegetable cultures, to improve fruit quality, sugar content, and stress resistance.

The method by which these fertilizers are introduced into the environment directly dictates the concentration and the spatial distribution of the corrosive agents around the foundation piles. Traditionally, solid granular fertilizers are broadcasted over the soil surface using mechanical spreaders. This solid application relies on subsequent rainfall or irrigation to dissolve the granules, creating concentrated pockets of highly aggressive electrolyte as the dissolved salts leach downward through the soil profile.

However, modern agricultural practices increasingly rely on fertigation, a technique where liquid fertilizers or highly soluble solid formulations are injected directly into the irrigation water [54]. Fertigation is distributed through center pivot systems, micro-sprinklers, or localized drip irrigation networks. This method is particularly critical from a corrosion standpoint. It ensures that the chemical compounds are already fully dissolved and highly mobile, allowing them to immediately permeate the soil matrix and wet the subterranean steel structures. In systems utilizing nebulization or foliar spray, the airborne chemical mist can deposit directly onto the above-ground metallic superstructure, creating an aggressive thin-film electrolyte that accelerates atmospheric corrosion.

The quantities of fertilizers released into the environment are massive compared to any natural mineral baseline. Depending on the crop requirements and soil depletion levels, the application rates of nitrogen can range from 50 to over 250 kilograms per hectare per year. For instance, intensive corn cultivation may require multiple applications resulting in local nitrogen concentrations that drastically reduce the electrical resistivity of the soil, often dropping it well below $20 \Omega \cdot \text{m}$ [21]. This massive influx of conductive ions transforms the soil into a highly efficient electrochemical cell.

Chemical attack kinetics on hot-dip galvanized steel

Hot-dip galvanized steel relies on a protective zinc coating that acts both as a physical barrier and a sacrificial anode. In natural, benign soils, zinc exhibits a low corrosion rate by forming a dense, adherent, and insoluble passive layer composed of zinc oxides, zinc hydroxides, and basic zinc carbonates. This passivity is thermodynamically stable within a specific neutral to slightly alkaline pH range, typically between 7 and 12 [17]. The introduction of nitrate and sulfate-based fertilizers completely disrupts this stability through two primary mechanisms: soil acidification and the formation of soluble complexes.

The application of ammoniacal nitrogen fertilizers, such as urea or ammonium nitrate, initiates a severe biological acidification process known as nitrification. When urea is applied, it is rapidly hydrolyzed by the enzyme urease into ammonia and carbon dioxide. Subsequently, specialized soil bacteria oxidize the ammonia first into nitrites and then into nitrates. The critical aspect of this biological oxidation is the massive release of hydrogen ions into the soil solution. The chemical equation for the overall nitrification process demonstrates this acidifying effect, where one mole of ammonium yields two moles of hydrogen ions.

This localized accumulation of hydrogen ions causes the pH of the soil pore water surrounding the foundation pile to drop significantly, often reaching acidic values between 4 and 5. Because zinc is an amphoteric metal, its passive carbonate layer is highly soluble in acidic environments. The hydrogen ions directly attack the zinc hydroxide and zinc carbonate films, dissolving them into aqueous zinc ions and water. Once the passive film is stripped away, the underlying active zinc is exposed directly to the aggressive soil electrolyte, and the anodic dissolution proceeds at an exponentially accelerated rate, driven by the cathodic reduction of the abundant hydrogen ions.

Furthermore, the presence of specific anions alters the corrosion kinetics. Nitrates act as strong oxidizing agents that can depolarize the cathodic reaction, facilitating a higher flow of corrosion current. Even more damaging is the presence of ammonia, which can react with zinc to form highly soluble zinc-ammine complexes. This complexation prevents the precipitation of any protective layer, leaving the surface continuously active.

Sulfates, introduced via fertilizers like potassium sulfate, participate in a different destructive kinetic. Sulfate ions are highly aggressive and possess the ability to penetrate and disrupt the semi-protective films on the zinc surface. When zinc reacts with sulfates, it forms zinc sulfate, which is highly soluble in water. Unlike basic zinc carbonates that seal the surface, zinc sulfate dissolves into the surrounding soil moisture and is washed away by irrigation or rainfall, continuously exposing fresh metal to the attack.

Under standard, non-agricultural conditions, the uniform corrosion rate of a hot-dip galvanized pile in soil can also reach 4 to 10 μm per year [17]. However, under the continuous chemical stress of fertigation with nitrates and sulfates, field studies and laboratory simulations indicate that the corrosion rate can easily increase, reaching peaks values of 20 to 40 μm per year or more, accompanied by severe localized pitting [54]. This accelerated kinetic drastically reduces the predicted service life of the foundation, potentially stripping the 80 μm zinc coating in less than a decade.

Chemical attack kinetics on weathering steel (Corten)

The use of weathering steel, or Corten, in underground applications is fundamentally flawed, and the presence of agricultural fertilizers exacerbates this vulnerability. Weathering steel achieves its superior atmospheric corrosion resistance through the formation of a tightly adherent, amorphous oxyhydroxide patina, fostered by alloying elements like copper, chromium, and phosphorus. The formation of this stable patina strictly requires alternating cycles of wetting and drying, along with abundant oxygen [36].

In the buried environment of an agrivoltaic foundation, the soil is continuously moist and poorly aerated. Under these conditions, the protective patina cannot form well, and Corten steel behaves electrochemically similarly to standard, unalloyed carbon steel. When exposed to the aggressive milieu of nitrate and sulfate fertilizers, the degradation kinetics become extremely severe.

The primary role of the dissolved fertilizer salts is to dramatically increase the electrical conductivity of the soil. The structural pile traverses different soil strata with varying oxygen concentrations, creating a macroscopic differential aeration cell. The highly conductive, fertilizer-rich moisture acts as a perfect electrolyte, allowing large galvanic currents to flow seamlessly between the oxygenated cathodic areas near the surface and the oxygen-deprived anodic areas deeper underground [19].

Furthermore, the acidification caused by the nitrification of ammonium fertilizers directly attacks the steel matrix. In acidic conditions, the predominant cathodic reaction shifts from oxygen reduction to hydrogen evolution. This process is not limited by the slow diffusion of oxygen through the waterlogged soil, allowing the anodic dissolution of iron to proceed at a very high velocity.

Sulfates also introduce the severe risk of microbiologically influenced corrosion. In the deeper, anaerobic zones of the soil, the abundant sulfates provided by the fertilizers serve as an electron acceptor for sulfate-reducing bacteria. These microorganisms metabolize the sulfates and excrete hydrogen sulfide, a highly toxic and corrosive compound. Hydrogen sulfide reacts directly with the iron in the Corten steel to form iron sulfide, creating deep, steep-sided pits that can rapidly perforate the structural thickness. While the standard uniform corrosion of carbon steel in benign soil might be around 0.05 mm per year, the combined effect of acidification, high conductivity,

and microbial activity driven by fertilizers can push the localized pitting rate of buried Corten well beyond 0.2 mm per year.

Chemical attack on the concrete of the foundations

When agrivoltaic structures require concrete plinths or micropile backfills due to poor soil mechanics, the concrete itself becomes a target for fertilizer-induced degradation. Concrete provides an initially highly alkaline environment that passivates the embedded steel rebars or the encased galvanized pile. However, the continuous exposure to sulfates and acidic nitrates severely compromises the chemical stability of the cementitious matrix.

The degradation mechanism caused by sulfates is known as sulfate attack, a well-documented and devastating chemical reaction in civil engineering [18]. The sulfate ions from the fertilizers penetrate the porous structure of the concrete and react with the calcium hydroxide, a primary hydration product of Portland cement, to form calcium sulfate, commonly known as gypsum. This reaction consumes the alkaline reserves of the concrete, lowering its pH and reducing its ability to protect the encased steel.

More critically, the sulfate ions also react with the calcium aluminate hydrates present in the cement paste to form ettringite. The crystallization of ettringite is a highly expansive volumetric reaction. As the ettringite crystals grow within the confined capillary pores of the hardened concrete, they generate immense internal tensile stresses. Because concrete has very low tensile strength, these internal pressures rapidly lead to micro-cracking, spalling, and the eventual disintegration of the external concrete cover.

Once the concrete cover is cracked by the expansive sulfate attack, the physical barrier protecting the foundation is breached. The acidic water containing nitrates, chlorides, and oxygen can now flow directly through the macroscopic cracks to reach the embedded steel pile or reinforcing bars. This initiates a severe localized corrosion cell. The steel exposed at the base of the crack becomes a small, active anode, while the passive steel still encased in the intact, alkaline concrete acts as a massive cathode. This unfavorable area ratio drives an extremely rapid dissolution of the metal at the crack location, leading to a swift structural failure of the foundation system.

4 Chapter 4: methodology and standards

4.1. Instrumentation

4.1.1. pH, conductivity, ORP meter and coating thickness gauges

To accurately assess the corrosivity of the soil and monitor the degradation of the agrivoltaic structures, a rigorous experimental campaign was conducted. The reliability of the data collected in the field and analyzed in the laboratory depends entirely on the precision, calibration and correct application of the measurement instrumentation. The assessment of the soil parameters required to calculate the total corrosion load, as defined by the DIN 50929-3 and ISO 12501 standards, necessitates the measurement of hydrogen ion concentration, electrical conductivity, and oxidation-reduction potential [46]. Concurrently, the evaluation of the structural degradation requires non-destructive testing of the residual protective zinc layer. This section details the technical specifications, the operating principles, and the calibration procedures of the instruments utilized during the research.

Multiparameter analysis: Apera PC60-Z for pH and electrical conductivity

To measure the acidity and the ionic concentration of the soil extracts, an Apera PC60-Z smart multiparameter tester was utilized. This instrument is designed to measure pH, electrical conductivity, total dissolved solids and salinity simultaneously.



Figure 8 - Apera PC60-Z for pH and electrical conductivity

The measuring head of the PC60-Z features a combined sensor design. For the pH measurement, it utilizes a highly sensitive glass bulb electrode that detects the potential difference generated by hydrogen ions across the glass membrane, referenced against a sealed internal silver/silver chloride half-cell. For the electrical conductivity measurement, it employs a platinum black electrode. The conductivity is determined by applying an alternating electrical current between two electrodes and measuring the resistance of the solution, which is then converted to conductivity based on the geometric cell constant of the probe.

The calibration of the PC60-Z is a critical step that was meticulously performed prior to each laboratory session. For the pH sensor, a two-point calibration was executed using standard buffer solutions at pH 4.00 and 7.00 to ensure the linearity of the response, in particular at acidic range. For the conductivity sensor, standard calibration solutions at 1413 $\mu\text{S}/\text{cm}$ and 12.88 mS/cm were utilized.

Comparing the instrument's capabilities with the expected field conditions confirms its suitability. The PC60-Z boasts a pH measurement range from -2.00 to 16.00 with an accuracy of ± 0.01 pH (± 1 digit). In the agrivoltaic context, the expected soil pH values range from highly acidic fertilizer-treated soils around pH 4.5 to slightly alkaline carbonated soils around pH 8.5. The instrument's range comfortably encompasses this spectrum. Regarding electrical conductivity, the instrument measures from 0 to 20.0 mS/cm with an accuracy of $\pm 1\%$ of the full scale (± 1 digit) [55]. In standard agricultural soils, conductivity typically fluctuates between 100 and 5000 $\mu\text{S}/\text{cm}$. These conductivity values are mathematically inverted and multiply with the correct conversion factor to obtain the specific soil resistivity expressed in $\Omega\cdot\text{cm}$, which is the primary input parameter for the DIN 50929-3 corrosion probability evaluation [17].

Oxidation-reduction potential: Apera ORP60

The measurement of the soil's oxidation-reduction potential, a fundamental parameter for assessing the degree of aeration and the risk of anaerobic bacterial corrosion, was conducted using an Apera ORP60 tester.



Figure 9 - Apera ORP60

The principle of the ORP measurement relies on a noble metal electrode, in this case, a high-quality platinum pin situated in the head of the instrument, paired with a silver/silver chloride reference electrode. The platinum pin serves as a passive sensor that accepts or donates electrons to the chemical species in the soil extract without participating in the reaction itself. The resulting electrical potential reflects the ratio of oxidizing agents (such as oxygen and nitrates) to reducing agents (such as organic matter and sulfides) in the sample [42] .

Calibration of the ORP60 differs from pH meters. It does not require a multipoint slope calibration but rather an offset verification using a specific redox standard solution with a reference value of 222 mV. If the instrument reading deviates from the standard, an offset adjustment is applied.

The working range of the ORP60 spans from -1000 to 1000 mV with a precision of ± 1 mV (± 1 digit). This extensive range is perfectly suited for the expected field variations. In superficial, well-drained, and aerated agrivoltaic soils, the potential is expected to be highly positive, ranging from +300 to +500 mV. Conversely, in the deep, waterlogged stratigraphies near the water table where oxygen is absent, the environment becomes reducing, and the potentials are expected to drop into the negative range, potentially down to -200 mV. Detecting these negative values is crucial, as the DIN 50929-3 standard associates highly negative redox potentials with the proliferation of sulfate-reducing bacteria, drastically increasing the predicted corrosion rate.

Coating thickness measurement: UNI-T UT343D

To evaluate the physical degradation of the foundations, it was necessary to quantify the remaining thickness of the protective zinc layer on the steel profiles. For this purpose, a UNI-T UT343D ultrasonic coating thickness gauge was employed.



Figure 10 - UNI-T UT343D ultrasonic coating thickness gauge [56]

The operating principle of this instrument is based on electromagnetic induction. The gauge generates a low-frequency magnetic field through a probe coil. When the probe is placed against the galvanized pile, the magnetic flux penetrates the non-magnetic

zinc coating and enters the underlying ferromagnetic carbon steel substrate. The instrument measures the magnetic reluctance or the change in magnetic flux density, which is directly proportional to the distance between the probe tip and the steel base. Because zinc is fundamentally non-magnetic, the instrument accurately interprets the thickness of the zinc layer as the non-magnetic gap [28].

The UT343D has a measurement interval from 0 to 1250 μm with a stated accuracy of $\pm(3\%H+1\mu\text{m})$. Standard hot-dip galvanized profiles used in agrivoltaics typically possess an initial zinc thickness ranging from 50 to 120 μm , depending on the steel thickness and silicon content. At these traditional galvanization ranges, the instrument's absolute precision is not optimal. For a coating of 50 μm , the expected error margin is around $\pm 2.5 \mu\text{m}$. While this tolerance might be considered high for precise micrometric laboratory studies, it remains a highly valuable numerical support for macroscopic field inspections over the long term. It allows engineers to track the progressive thinning of the sacrificial layer over decades, clearly distinguishing between a pile that retains 60 μm of zinc and one that has been depleted to 10 μm in the critical air-soil transition zone [57].

The most challenging aspect of utilizing the UT343D in the field is the calibration process. Electromagnetic induction gauges require a zero-point calibration to ensure accuracy. According to international testing norm ISO 2178, this zeroing process absolutely requires a bare, uncoated sample of the identical substrate metal used in the structure, possessing the same magnetic permeability and surface roughness. Obviously, extracting a section of bare steel from an active, fully coated agrivoltaic pile is structurally unfeasible.

To circumvent this limitation, specific strategies were adopted during the field campaign. In newly constructed sites, it was occasionally possible to find spare, un-driven piles. A small section of these spare profiles was mechanically ground down to the bare steel core to serve as an in-situ zero reference. For sites where bare steel from the actual batch was unavailable, the calibration was performed relying on the reference plates prepared for different specification (e.g. S235JR or S355JR).

4.2. Inspection protocol

4.2.1. Excavation procedure of air-soil transition zone

The definition of a field inspection protocol within the context of this experimental campaign required a careful balance between the pursuit of exhaustive scientific data and the practical, safety and economic limitations inherent to the operation and maintenance of an active agrivoltaic plant. From a purely academic and geotechnical perspective, the ideal investigation of a foundation pile's corrosion status would involve an analysis over its entire driven depth. This would require continuous core

drilling parallel to the pile, complete stratigraphic logging and soil sampling at multiple discrete heights down to 3 or 4 m, similar to the procedures utilized during the preliminary design phase [58]. However, such an approach requires heavy machinery, significant costs and the interruption of agricultural activities, making it entirely unsuitable for periodic monitoring.

Therefore, the primary objective of this specific phase of the research was to develop and validate a simplified, manual excavation procedure. This protocol had to be easily transferable to standard maintenance technicians for routine periodic checks, utilizing basic instrumentation, while still providing reliable data regarding the structural health of the foundation.

To achieve this, the investigation deliberately focused on the most vulnerable sector of the foundation: the air-soil transition zone. As established in the theoretical analysis of underground corrosion, the area immediately below the ground level is where the differential aeration cell reaches its maximum aggressive potential, driven by the steep oxygen concentration gradient between the atmosphere and the subsoil [42]. Furthermore, this shallow layer is where agricultural fertilizers accumulate, drastically lowering the electrical resistivity and the pH of the soil pore water.

While the theoretical ideal depth for inspecting this transition zone is between 30 and 50 cm, the practical execution of the field tests demonstrated the necessity of adapting this target. During the experimental campaign, the manual excavations were systematically halted at a depth of approximately 20 to 30 cm. This operational limit was dictated by a convergence of three distinct practical factors.

Firstly, the physical limitation of the hand tools utilized; a standard trenching spade allows for an efficient and ergonomically safe excavation only up to about 30 cm before the lever angle becomes impractical for a single operator working close to a sensitive solar tracker structure. Secondly, the geotechnical nature of the agricultural topsoil presented a significant challenge. The superficial soil in agrivoltaic contexts is frequently plowed and lacks cohesion. Digging a narrow, deep hole around a driven pile invariably leads to the continuous auto-collapse of the trench walls. Without the installation of temporary shoring, which would violate the requirement for a rapid and simple procedure, maintaining a clean excavation beyond 30 cm proved unfeasible. Thirdly, the hydrogeological conditions during the specific period of the sampling campaign strongly influenced the depth. In many investigated sites, particularly in the Po Valley area, the seasonal water table or the agricultural irrigation water perched upon shallow impermeable clay lenses was extremely high. Excavating deeper than 30 cm frequently resulted in the immediate flooding of the test pit. The presence of standing water not only prevents the extraction of an undisturbed soil sample for moisture and resistivity analysis but also makes it completely impossible to properly clean the surface of the steel pile to perform the necessary ultrasonic

coating thickness measurements described in the subsequent sections of the methodology.

Despite these deliberate methodological simplifications and depth constraints, the validity of the data collected was rigorously verified. The physical-chemical values measured from the shallow samples, such as pH, electrical conductivity and redox potential, were compared against official, deep geotechnical and geochemical analyses previously commissioned by the plant owners during the authorization phase of the sites. These official baseline reports were conducted strictly following the rigorous dictates of the DIN 50929-3 standard for evaluating the corrosion likelihood of buried structures [46].

The comparison revealed that the values measured through the simplified 20-30 cm excavation protocol were not significantly discordant from the official baseline data. A certain margin of deviation was expected and is considered entirely acceptable in geotechnical engineering. This margin is physiologically justified by the different periods of sampling, since soil moisture and fertilizer salt concentrations fluctuate wildly with seasonal rains and agricultural cycles and by the slightly different spatial positioning of the sampling points, given that soil is a highly heterogeneous medium even within a few meters [51]. The correlation was strong enough to confirm that the shallow sampling adequately captures the worst-case corrosive load acting on the transition zone of the pile, effectively validating the simplified protocol for maintenance purposes.

Regarding the spatial distribution of the investigation, the protocol standardized the execution of 5 separate excavations for each agrivoltaic plant analyzed (+3 every 10mw over first 10mw). This number was selected to provide a statistically significant representation of the site without inducing excessive operational burdens. The 5 points were not chosen randomly; they were equitably distributed across the plant layout, taking into specific consideration the morphological variations of the terrain, such as localized depressions where water might stagnate, areas with different crop typologies, and specific indications provided by the plant owners who had historical knowledge of the field's behavior.

The methodology developed and tested in this campaign finds strong parallel validation in the official maintenance guidelines published by major steel manufacturers. A critical reference in this context is the technical documentation provided by Wuppermann, a leading producer of the advanced zinc-aluminum-magnesium alloy pre-galvanized coils widely used in modern photovoltaic profiles. In order to satisfy the conditions of their long-term warranties against structural perforation, which can extend up to 25 years, Wuppermann mandates a strict periodic inspection regime [32],[59].

A deep dive into the Wuppermann warranty guidelines reveals a direct correspondence with the simplified excavation method proposed in this thesis. The manufacturer explicitly requires a visual and instrumental inspection of the buried portion of the piles every 1 (visual) and 5 (residual thickness) years. This requirement is rooted in the acknowledgment that the initial soil corrosivity parameters, classified according to the DIN 50929-3:2018 standard during the design phase, can mutate due to external environmental factors or changes in agricultural management.

The Wuppermann guidelines dictate that the soil must be removed from around a representative sample of 0.2% of piles to expose the interface zone for a depth of 20cm. The purpose of this excavation is to verify the behavior of the self-healing zinc-magnesium layer, specifically looking for the presence of the stable white rust patina and ensuring the absence of red rust originating from the carbon steel core, which would indicate a premature depletion of the sacrificial coating. Furthermore, the guidelines require the measurement of the residual coating thickness in this exposed area.

The normative framework underpinning these manufacturer requirements, such as the ISO 1461 standard for hot-dip galvanized coatings and the ISO 12501 standard for soil corrosivity, implicitly supports the necessity of continuous monitoring when structures are placed in environments categorized as Im3 (buried in soil) with agricultural chemical variables [28].

Therefore, the excavation procedure of 20 to 30 cm developed in this campaign is not merely an academic exercise constrained by practical limits; it represents the exact operational translation of the manufacturer's warranty requirements. By demonstrating that a shallow, carefully executed manual excavation can yield reliable soil corrosivity data and allow for accurate coating thickness measurements at the most critical point of the pile, this protocol provides operations and maintenance teams with a standardized, standard-compliant and economically viable tool. It bridges the gap between the complex theoretical models of soil corrosion defined by DIN 50929-3 and the practical necessity of ensuring the structural safety of the agrivoltaic plant over its 30-year design life.

4.2.2. Cleaning methods and residual thickness measurement

Following the excavation procedure described in the previous section, the exposed underground portion of the foundation pile is inevitably coated with a thick layer of adhered soil, mud and agricultural residues. Before any reliable qualitative or quantitative assessment of the corrosion status can be performed, the surface must be rigorously cleaned. The methodology applied during this delicate phase is of paramount importance, as an overly aggressive cleaning protocol could inadvertently remove the residual protective coating or the fragile corrosion products, thereby falsifying the subsequent instrumental readings and visual analyses.

To preserve the true state of the surface, the removal of the earth was executed strictly using non-aggressive mechanical methods. The macroscopic clods of soil were gently detached using plastic spatulas, followed by brushing with soft, synthetic bristle brushes. The use of carbon steel or brass wire brushes, which are common in heavy construction maintenance, was expressly prohibited in this protocol. Metallic bristles possess a hardness far superior to that of the zinc layer and the basic zinc carbonates (white rust) formed on the surface; their use would inevitably scratch the protective barrier, removing micrometers of healthy galvanization and compromising the structural evaluation [28]. After the dry brushing, the interface was rinsed using tap water applied via a low-pressure manual sprayer to dissolve the remaining clay particles. Finally, the surface was dried using a clean, lint-free microfiber cloth.

Once the residues were completely removed, the first analytical step consisted of a systematic visual inspection. Visual analysis, when conducted with methodological rigor, provides immediate critical insights into the prevalent corrosion morphology. To ensure the reproducibility and comparability of the data across the various investigated sites, the visual inspections were standardized. A high-intensity portable led light was utilized to illuminate the excavated cavity, highlighting surface irregularities, pitting craters and chromatic variations. A metric reference scale (a rigid metallic ruler) was always positioned adjacent to the cleaned pile face to allow for accurate photographic cataloging. The photographic documentation serves as the qualitative baseline, capturing the distribution of white rust (zinc oxidation), the potential emergence of red rust (iron oxidation indicating the total depletion of the sacrificial layer) and the presence of localized blistering or mechanical damage inflicted during the pile driving phase [37].

In conjunction with the visual assessment, a quantitative measurement of the residual coating thickness was performed on the galvanized steel structures utilizing the UNIT UT343D ultrasonic/electromagnetic coating thickness gauge. The measurement was not limited to a single random point, which could be statistically irrelevant due to microscopic surface roughness or localized anomalies. Instead, a standardized sampling matrix was established. Within the excavated hole, on the face of the pile exhibiting the most severe visual degradation, a reference area of approximately 10 by 10 cm was delineated. Within this specific quadrant, five distinct measurements were taken (typically one at each corner and one in the geometric center). The arithmetic mean of these five readings provides a highly reliable representation of the generalized thickness loss in the deeply buried zone.

To properly contextualize the degradation of the buried section, the protocol mandates a comparative analysis with the above-ground portions of the same pile. Therefore, the same 5-point measurement matrix was replicated at two additional specific elevations: at 20 cm above the ground level and at 100 cm above the ground level. The measurement at 100 cm serves as the baseline reference. At this height, the steel profile

is exposed exclusively to the atmospheric environment (typically corrosivity class C2 or C3), well above the reach of agricultural splash, capillary rising damp, and direct contact with fertilizers. The thickness recorded here represents the original factory galvanization minus the negligible atmospheric consumption occurred over the plant's operational years. The measurement at 20 cm investigates the upper boundary of the splash zone. This area is subjected to the aggressive action of rebounding rainwater mixed with topsoil and fertilizers, representing a transitional environment where the degradation is usually more severe than the pure atmosphere but less aggressive than the permanent burial.

The fundamental engineering value derived from this multi-level approach is the relative corrosion delta. As discussed regarding the instrumentation, ultrasonic gauges based on magnetic induction require a zero-point calibration on the bare substrate. Because it is impossible to strip a working pile down to bare steel just for calibration, the compatibility of the instrument's standard calibration block with the actual magnetic permeability of the specific S355 steel pile is evaluated case by case, inevitably introducing a slight absolute offset error. However, by comparing the measurements taken at 100 cm, 20 cm, and 30 cm on the exact same pile, this calibration offset mathematically cancels itself out. The resulting difference, or delta, provides the absolute material loss caused specifically by the underground environment. If the pile measures 75 μm at 1 m above ground and 40 μm in the excavated hole, the delta of 35 μm represents the unquestionable consumption driven by the differential aeration cell and the soil chemistry, regardless of the absolute zero-calibration perfection.

The excavation and cleaning protocol was specifically adapted for structures utilizing concrete foundations, such as micropiles or concrete plinths. In these scenarios, the manual excavation terminates upon reaching the upper surface of the concrete casting. The cleaning procedure is then extended horizontally, parallel to the ground level, to completely expose the concrete collar surrounding the steel profile. The inspection at this specific interface is critical. The visual analysis focuses on identifying any macroscopic cracks in the concrete radiating outward from the steel pile. Such cracking is frequently symptomatic of expansive corrosion products; as the steel rusts, the iron oxides occupy a volume up to six times greater than the original metal, exerting massive tensile stresses that easily split the concrete cover [18]. Furthermore, the interface ring between the concrete and the steel profile is meticulously probed to detect gaps, detachments, or the infiltration of stagnant water. As defined in corrosion science, a poorly sealed concrete-steel interface creates a perfect crevice, trapping moisture and aggressively lowering the local pH, which rapidly initiates localized attack on the zinc coating exactly at the base of the structure [42].

Finally, specific mechanical testing procedures were integrated into the protocol to evaluate advanced stages of degradation, particularly for piles made of weathering steel (Corten) and for galvanized piles where the zinc has been completely consumed,

leaving the carbon steel heavily oxidized. Unlike zinc, which forms a dense, adherent, and protective passive film, the corrosion of carbon steel in the continuously damp, unaerated underground environment produces a porous, non-adherent layer of rust (primarily lepidocrocite and magnetite) that offers no barrier protection [36]. To qualitatively assess the structural integrity of this oxidized layer, a tape adhesion test, conceptually derived from the ASTM A588 standard for coating adhesion, was performed. A strip of high-adhesion woven duct tape is applied firmly to the dried, corroded surface within the excavation and rapidly peeled off. The evaluation is based on the detachment of the material; if the tape removes thick, heavy flakes of rust or abundant oxidized powder, it confirms that the macroscopic patina is completely non-protective and structurally useless. Following the tape test, a sharp, pointed steel tool (such as an awl or a geological pick) is utilized to physically probe the porosity of the underlying material. By applying localized pressure, the operator evaluates the tendency of the steel to release deep scales. More importantly, the pointed tool is used to search for the presence of deep pitting craters hidden beneath the voluminous rust flakes. Since underground corrosion on unalloyed steel proceeds almost exclusively through localized autocatalytic pitting rather than uniform dissolution, finding soft, penetrable spots with the probe indicates severe localized loss of structural cross-section, a critical failure mechanism widely documented in historical geotechnical corrosion studies [19].

4.3. Physico-chemical soil analysis

4.3.1. Calculation of soil aggressivity rating according to DIN 50929-3

The structural dimensioning of an agrivoltaic foundation system cannot be separated from a rigorous evaluation of the physical and chemical properties of the ground. Historically, geotechnical campaigns conducted prior to the construction of solar plants have focused almost exclusively on the mechanical capacity of the soil. Specialized geologists are routinely employed to perform standard penetration tests, analyze seismic wave velocities and execute pull-out tests to determine the bearing capacity and the friction angle of the soil to ensure structural stability against wind and snow loads [58]. While these mechanical parameters are critical to prevent immediate structural collapse, they provide absolutely no information regarding the electrochemical aggressiveness of the environment over the 25 to 30 years of the plant's operational life.

This purely mechanical approach represents a critical gap in the engineering process. It is imperative that the preliminary geotechnical campaign integrates a comprehensive physico-chemical analysis of the soil. This analysis must be carried out by specialized personnel concurrently with the mechanical testing, utilizing the exact same test pits or boreholes to extract undisturbed soil samples [60]. To quantify the

corrosion risk accurately, the European scientific community and major steel manufacturers rely on the German standard DIN 50929-3. This standard provides a highly detailed, multifactorial framework for calculating the likelihood of corrosion on buried metallic structures based on specific, weighted variables, far surpassing the simplified bivariate approach of the ISO 12501 standard [51].

The DIN 50929-3 evaluation framework: distinguishing between B and W indices

The DIN 50929-3 standard approaches the complexity of the underground environment by recognizing that a single metallic structure, such as an photovoltaic driven pile, traverses multiple distinct corrosive zones. To accurately predict the degradation, the standard defines different indices based on the specific material and the physical state of the surrounding electrolyte, differentiating between moist soil and liquid water. The primary indices utilized are B_0 , B_1 , B_D , W_0 , W_1 , W_D and W_L .

The fundamental index for evaluating soil corrosivity is the B_0 value. This value represents the expected corrosion load for free corrosion in the absence of extensive macroscopic concentration cells. It is calculated by algebraically summing specific soil parameters, designated as Z factors. The resulting B_0 score classifies the homogeneous soil into categories ranging from practically non-corrosive to highly corrosive [46]. The B_0 parameter is strictly calibrated for unalloyed and low-alloy ferrous materials. Therefore, it is the perfect indicator for assessing the risk to weathering steel, commercially known as Corten. Because Corten cannot form its protective atmospheric patina underground, its degradation rate in the soil is directly proportional to the B_0 classification.

$$B_0 = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 + Z_7 + Z_8 + Z_9 + Z_{10}$$

However, soils are rarely perfectly homogeneous. A deep pile often crosses different geological strata with varying degrees of aeration and moisture. To account for this, the standard introduces the B_1 index. The B_1 value evaluates the free corrosion in the presence of extensive concentration cells. It is calculated by taking the base B_0 value and adding additional Z parameters which quantify vertical and horizontal heterogeneity.

$$B_1 = B_0 + Z_{11} + Z_{12} + Z_{13} + Z_{14}$$

For a long Corten pile, a highly negative B_1 value indicates a severe risk of localized pitting driven by galvanic currents flowing between different soil layers.

Table 1 - classification of soils, corrosion load and likelihood of free corrosion of unalloyed and low-alloy ferrous materials [extracted from DIN 50929-3:2018, Table 3]

B_0 or B_1 values	Soil category	Corrosion load ^a	Likelihood of corrosion based on the B_1 value	
			Pitting corrosion	Uniform corrosion
≥ 0	Ia	very low	very low	very low
-1 to -4	Ib	low	low	very low
-5 to -10	II	medium	medium	low
< -10	III	high	high	medium
The order of magnitude of the corrosion rate to be expected is specified in Table 1. In the case of pipes and tanks, priority shall be given to the assessment of permanent leak tightness. In this case, the rate of pitting corrosion is to be considered. In the case of structural components, priority shall be given to the assessment of permanent strength. In this case, the rate of uniform corrosion is to be considered.				
^a The corrosion load corresponds to the likelihood of free corrosion in the absence of extensive concentration cells (see 6.1.2).				

When considering hot-dip galvanized steel, the evaluation shifts. Zinc is a highly reactive metal that behaves differently from carbon steel. While the standard uses the Z parameters to define the environment, the specific assessment of galvanized coatings in soil relies on derived indices, such as the B_D assessment.

$$B_D = Z_2 + Z_4 + Z_5 + Z_6 + Z_7$$

The longevity of the zinc coating is heavily penalized by sudden drops in resistivity and pH, which dissolve the passivating zinc carbonate layer much faster than the underlying steel would corrode.

Table 2 - Rating of coatings on hot-dip galvanized steels [extracted from DIN50929-3:2018, Table 6]

B_D, W_D, W_L values of the anode	Pitting corrosion
≥ 0	very good
-1 to -4	good
-5 to -8	satisfactory
< -8	not adequate

Table 3 - Information relating to the assessment of soil [extracted from DIN50929-3:2018, Table 2]

Z	Parameters / Measurands	Requirement or criterion	Test	Unit	Measurement range	Rating
	soil samples					
Z ₁	type of soil — cohesion	proportion of elutriable matter	method as in: DVGW GW 9:2011-09, Annex B, Module 5	mass fractions in %	< 10	4
					10 to 30	2
					30 to 50	0
					50 to 80	-2
					> 80	-4
	— contamination	DIN EN 12501-2:2003-08 Table 1				-12
Z ₂	specific electrical soil resistivity	lowest resistivity after addition of water, measured in the cell	method as in: DVGW GW 9:2011-09, Annex B, Module 2	Ω m	> 500	4
					200 to 500	2
					50 to 200	0
					20 to 50	-2
					10 to 20	-4
					< 10	-6
Z ₃	moisture content of soil and reference for Z ₆ to Z ₁₀	water content after drying at 105 °C	method as in: DVGW GW 9:2011-09, Annex B, Module 1	mass fractions in %	< 20	0
					> 20	-1
Z ₄	pH value	pH value for 50% water content	method as in: DVGW GW 9:2011-09, Annex B, Module 2	—	> 9	2 ^a
					6 to 9	0
					4 to 6	-1
					< 4	-3
Z ₅	buffer capacity — alkalinity K _{S 4.3}	acidity up to pH = 4.3	method as in: DVGW GW 9:2011-09, Annex B, Module 4	mmol/kg	> 1000	3
					200 to 1000	1
					< 200	0
Z ₆	buffer capacity — acidity K _{B 7.0}	alkalinity up to pH = 7.0	method as in: DVGW GW 9:2011-09, Annex B, Module 5	mmol/kg	< 2.5	0
					2.5 to 5	-2
					5 to 10	-4
					10 to 20	-6
					20 to 30	-8
					> 30	-10
Z ₇	sulfate-reducing bacteria	sulfide content	method as in: DVGW GW 9:2011-09, Annex B, Module 6	mg/kg	< 5	0
					5 to 10	-3
					> 10	-6

Z ₈	sulfate content	sulfate content	method as in: DVGW GW 9:2011-09, Annex B, Module 4	mmol/kg	< 2	0
					2 to 5	-1
					> 5 to 10	-2
					> 10	-3
Z ₉	neutral salt	chloride and sulfate content in aqueous extract	method as in: DVGW GW 9:2011-09, Annex B, Module 3	mmol/kg	< 3	0
					3 to 10	-1
					10 to 30	-2
					30 to 100	-3
					> 100	-4
	location conditions					
Z ₁₀	location of structure with respect to groundwater	groundwater present	visual inspection	—	never	0
					always	-1
					temporarily	-2
Z ₁₁	soil homogeneity horizontal by means of soil resistance profile	fluctuations in soil resistance	method as in: DVGW GW 9:2011-09, Annex A	—	$ \Delta Z < 2$	0
					$2 \leq \Delta Z \leq 3$	-2
					$ \Delta Z > 3$	-4
Z ₁₂	soil homogeneity vertical	different soil resistances	method as in: DVGW GW 9:2011-09, Annex A	—	$ \Delta Z < 2$	0
					$2 \leq \Delta Z \leq 3$	-1
					$ \Delta Z > 3$	-2
Z ₁₃	soil homogeneity — bedding	soil of similar type or sand	visual inspection	—	homogeneous	0
		components foreign to soil, such as wood, roots or soils with characteristics as in DIN EN 12501-2:2003-08, Table 1			inhomogeneous	-6
Z ₁₄	soil homogeneity — different pH values	anthropogenic influences	method as in: DVGW GW 9:2011-09, Annex B, Module 2	—	$ \Delta Z_4 < 1.5$	0
					$ \Delta Z_4 \geq 1.5$	-6
Z ₁₅	presence of external cathodes	structure/soil potential U _{Cu} /CuSO ₄	method as in: DVGW GW 9:2011-09, Annex A	V	< -0.5	0
					-0.5 to -0.4	-3
					-0.4 to -0.3	-8
					> -0.3	-10
^a Only in the case of homogeneous bedding. For inhomogeneous bedding (different pH values) Z ₁₄ applies.						

The standard also meticulously addresses situations where the foundation is located in areas with a very high water table or submerged in flooded agricultural basins. In these completely immersed conditions, the soil parameters (Z factors) are no longer applicable and are replaced by water parameters (W factors). The index W_0 defines the likelihood of free corrosion for a structure completely immersed in homogeneous water.

$$W_0 = N_1 + N_3 + N_4 + N_5 + N_6 + \frac{N_3}{N_4}$$

The index W_1 expands this to account for water/air interface at the water body.

$$W_1 = W_0 - N_1 + N_2 \cdot N_3$$

Crucially, the standard dictates that for unalloyed steel (Corten), the evaluation utilizes the N parameters. Conversely, because of the differing properties of zinc, the corresponding M parameters must be used to assess the quality of protective galvanized coatings under water.

Table 4 - estimating the likelihood of corrosion of unalloyed and low-alloy steels in water
[extracted from DIN50929-3:2018, Table 8]

W_0 or W_1 values	Pitting corrosion	Uniform corrosion
≥ 0	very low	very low
-1 to -4	low	very low
< -4 to -8	medium	low
< -8	high	medium
The order of magnitude of the corrosion rate to be expected is specified in Clause 5.		

Finally, the standard identifies the most critical sector of any partially buried structure with a zinc coating: the W_L index. This index specifically evaluates the predominantly localized corrosion at the water/air interface [46]. The W_L parameter mathematically embodies the differential aeration cell. It quantifies the extreme localized attack that occurs exactly at ground level, where the steel is simultaneously exposed to atmospheric oxygen, acting as the cathode and conductive water table, acting as the anode.

$$W_L = M_1 + M_2 + M_3 + M_4 + M_5 + M_6$$

For both Corten and galvanized steel, the W_L evaluation invariably represents the highest risk of structural failure due to rapid cross-sectional reduction, commonly known as necking.

Table 5 - Information relating to the assessment of water [extracted from DIN50929-3:2018, Table 7]

No.	Parameters/Measurands	Unit	Rating for unalloyed steel (Ni)	Rating for galvanized steel (Mi)
1	Type of water		N ₁	M ₁
	flowing water		0	-2
	standing water		-1	1
	water near the shore of lakes		-3	-3
	anaerobic fen water, coastal water		-5	-5
2	Location of structure		N ₂	M ₂
	under water		0	0
	water/air interface		1	-6
	splash zone		0,3	-2
3	$c(Cl^-)+2c(SO_4^{2-})$	mol/m ³	N ₃	M ₃
	≤1		0	0
	>1 to 5		-2	0
	>5 to 25		-4	-1
	>25 to 100		-6	-2
	>100 to 300		-7	-3
	>300		-8	-4
4	Acidity up to pH = 4,3 (alkalinity K _{S 4,3})	mol/m ³	N ₄	M ₄
	<1		1	-1
	1 to 2		2	1
	>2 to 4		3	1
	>4 to 6		4	0
	>6		5	-1

5	$c(\text{Ca}^{2+})$	mol/m ³	N ₅	M ₅
	<0,5		-1	0
	0,5 to 2		0	2
	>2 to 8		1	3
	>8		2	4
6	pH value		N ₆	M ₆
	<5,5		-3	-6
	5,5 to 6,5		-2	-4
	>6,5 to 7,0		-1	-1
	>7,0 to 7,5		0	1
	>7,5		1	1
7	Structure/water potential U _H (for detecting external cathodes)	V	N ₇	
	>-0,2 to -0,1		-2	
	>-0,1 to 0,0		-5	
	>0,0		-8	

Common measurands: the chemical intersection of Z, N, and M parameters

A superficial reading of the DIN 50929-3 standard might suggest that soil corrosion (evaluated via Z parameters) and water corrosion (evaluated via N and M parameters) are entirely disconnected phenomena. However, the fundamental electrochemical principles driving the degradation are identical. The parameters Z, N, and M are merely different quantifications and scorings of the exact same chemical measurands, adjusted for the physical matrix (solid soil versus liquid water) and the specific metallurgy of the target material (unalloyed steel versus zinc). Focusing on these common measurands provides a much deeper understanding of the environmental aggressiveness, especially regarding parameters that can be easily monitored in the field.

Hydrogen ion concentration (pH value)

The pH value is the most universally recognized indicator of environmental aggressiveness. It measures the concentration of hydrogen ions in the electrolyte. In

the standard, this measurand is evaluated as Z_4 for soil extracts, N_6 for unalloyed steel in water, and M_6 for galvanized steel in water.

Most natural agricultural soils hover around a neutral pH, scoring a neutral 0 in the Z_4 category. However, the application of nitrogen-based fertilizers initiates a biological nitrification process that releases massive amounts of hydrogen ions, drastically dropping the local pH. When evaluating this acidified condition in a high water table scenario, the scoring reveals the distinct vulnerabilities of the materials. According to the standard, for an unalloyed steel or Corten pile immersed in water with a pH below 5.5, the N_6 parameter assigns a penalty of -3. This negative score reflects the fact that in acidic conditions, the protective iron oxides dissolve, and the cathodic reaction shifts from oxygen reduction to rapid hydrogen evolution, accelerating the anodic dissolution of the iron. However, for a hot-dip galvanized pile in the exact same water, the corresponding M_6 parameter assigns a massive penalty of -6 [46]. This doubled penalty is not arbitrary; it is a direct quantification of zinc's amphoteric nature. Zinc relies entirely on a microscopic layer of zinc hydroxide and zinc carbonate for passivity. This layer is thermodynamically unstable and highly soluble at a pH below 6.0. Therefore, a slight drop in pH that might only moderately increase the rusting of a Corten pile will catastrophically strip the zinc coating from a galvanized pile, leaving the underlying steel completely unprotected. From a field inspection perspective, pH is easily measurable using a portable multiparameter tester on a soil-water extract, making it a critical leading indicator for maintenance planning.

Chlorides and sulfates concentration

The presence of dissolved salts transforms the underground environment into a highly conductive electrolyte, facilitating the rapid flow of galvanic currents. Furthermore, specific anions possess the ability to actively destroy passivating films. In the standard, these measurands are evaluated separately in soil as Z_7 (chlorides) and Z_8 (sulfates), while in water, they are mathematically combined into an equivalent concentration formula, evaluated as N_3 for unalloyed steel and M_3 for galvanized steel.

Sulfates and chlorides are continuously introduced into agrivoltaic soils through fertilization. Chlorides are notorious for penetrating the protective oxide films on both zinc and steel, initiating deep, autocatalytic pitting craters. Sulfates act as strong depassivators and, critically, serve as the primary nutrient for anaerobic sulfate-reducing bacteria in deep, waterlogged soils. When evaluating these ions in an immersed condition, the standard uses the combined molar concentration formula:

$$3 \cdot c(Cl^-) + 2 \cdot c(SO_4^{2-})$$

The resulting score highlights a fascinating metallurgical divergence. If this combined concentration is extremely high (greater than 300 mol/m^3), the N_3 parameter for unalloyed Corten steel assigns an extreme penalty of -8. This massive deduction indicates that bare steel is highly susceptible to rapid, generalized destruction and

severe pitting in hyper-saline environments. Conversely, for galvanized steel, the corresponding M_3 parameter for the same high concentration assigns a penalty of only -4 [46]. This indicates that while zinc is undoubtedly damaged by high chlorides and sulfates (often forming soluble zinc chlorides that wash away), it possesses a slightly higher relative resilience to pure salinity compared to bare steel, provided the pH remains alkaline or neutral. The zinc sacrifices itself uniformly rather than allowing the deep, structural pitting that would rapidly perforate an unalloyed Corten pile.

Buffer capacity (alkalinity and acidity)

The buffer capacity represents the environment's ability to resist drastic changes in pH when acidic or basic substances are introduced. In dynamic agrivoltaic environments, where acidic fertilizers and alkaline soil amendments are frequently applied, a high buffer capacity acts as a chemical shock absorber. In soil, this is evaluated through parameters Z_5 and Z_6 . In water, the corresponding measurand is the acidity up to pH 4.3, evaluated as N_4 for unalloyed steel and M_4 for galvanized steel.

If the water has a high buffering capacity, meaning it requires a significant amount of acid to lower its pH to 4.3, it provides a stable environment. The standard assigns slightly positive scores (+1) for moderate buffer capacities for both N_4 and M_4 [46]. This stability prevents the sudden pH crashes that are so destructive to the amphoteric zinc coating and the protective rust layers on Corten. However, unlike pH and simple conductivity, determining the buffer capacity requires complex laboratory titration. Therefore, while conceptually critical, it is not a parameter that can be easily integrated into routine field inspections by maintenance technicians.

Calcium ion concentration

The concentration of dissolved calcium is a measurand specifically highlighted in the water evaluation tables, represented by N_5 for unalloyed steel and M_5 for galvanized steel. Calcium plays a profoundly protective role in aqueous corrosion.

In groundwater with sufficient temporary hardness, the cathodic reduction of oxygen produces hydroxyl ions, which locally increase the pH at the metal surface. This localized alkalinity causes the dissolved calcium to precipitate as a dense, adherent layer of calcium carbonate directly onto the steel or zinc profile. This calcareous scale acts as an exceptional physical barrier, smothering the cathodic sites and virtually stopping the corrosion process. The standard heavily rewards the presence of calcium. For an unalloyed Corten pile, a high calcium concentration (greater than 8 mol/m³) yields an N_5 score of +2. However, for a galvanized pile, the corresponding M_5 score is an outstanding +4 [46]. This significant protective rating reflects the fact that calcium carbonate precipitates exceptionally well over the basic zinc carbonate patina, sealing the sacrificial layer and exponentially extending the life of the galvanized coating in submerged conditions.

Specific electrical resistivity and conductivity

While explicitly detailed as Z_2 for soil, the specific electrical resistivity is the master variable that underpins all electrochemical degradation. In water evaluations, this concept translates directly to electrical conductivity. Resistivity dictates the electrical resistance offered to the flow of galvanic corrosion currents between the anodic and cathodic areas of the pile.

The standard assigns highly positive scores to extremely resistive soils, as they physically impede the corrosion cell. However, as resistivity drops below $1000 \Omega \cdot \text{cm}$, usually due to the massive influx of fertilizer salts, the Z_2 parameter incurs a heavy penalty of -6 [46]. This parameter is the most easily and instantly measurable factor in the field, using a portable conductivity meter on a soil-water extract. A sudden spike in conductivity detected during a routine maintenance check is the clearest warning sign that the corrosivity category of the site has temporarily jumped, accelerating the consumption of the structural foundations.

Practical evaluation of risk factors and field expectations

The multifactorial structure of the DIN 50929-3 standard, integrating Z , N , and M parameters, demonstrates that an agrivoltaic foundation is not a static system. Its environmental load fluctuates drastically over the seasons, making the initial geological assessment just a starting point.

Consider a baseline agricultural field in a dry state before planting. The soil might present a sandy-loam texture, high resistivity, low moisture, and a neutral pH, with negligible sulfates and chlorides. This scenario perfectly mirrors the actual data collected from the Padova site, where laboratory tests revealed a pH of 7.5, negligible sulfides and chlorides and high resistivity [61]. The resulting calculations yield a B_0 score classifying the soil as "weakly aggressive". In this specific situation, the risk is minimal. For an unalloyed Corten pile, the corrosion rate would be slow. For a galvanized pile, the standard zinc coating would easily survive the 30-year design life without requiring additional protection.

However, the operating conditions of an agrivoltaic plant transform this baseline. Once intensive fertigation commences, the environment is radically altered. If we examine a site like Vercelli, the geotechnical report identifies a shallow water table, meaning the lower portion of the pile is permanently evaluated under the W_0 immersed conditions using N and M parameters. The chemical analyses highlight significant chemical loading, with sulfate contents reaching alarming peaks of 500 mg/Kg [58].

In case of active agricultural condition, the field parameters can shift dramatically. The massive influx of salts plummets the electrical resistivity. The biological nitrification of the fertilizers drops the local pH. Under these conditions, the calculation of the overall aggressivity index plummets into the "highly corrosive" categories. In this new

risk category, the expected values of material loss change exponentially. Manufacturer guidelines for advanced pre-galvanized alloys operating in highly corrosive soils indicate that the theoretical lifetime of a thin coating might drop to a mere 10 years [62]. For a Corten steel pile, this implies an aggressive pitting attack that could easily exceed 0.1 mm per year, leading to rapid structural perforation.

This mathematical category jump illustrates exactly why the initial physico-chemical analysis by a specialized geologist is mandatory and why relying solely on mechanical pull-out tests ignores the chemical reality of the soil. Furthermore, it highlights the absolute necessity of establishing a continuous monitoring protocol for the easily measurable parameters, primarily conductivity and pH. By tracking these specific measurands in the critical air-soil transition zone (W_L) and in the deep immersed zone (W_0) during the wet season, engineers can predict the accelerated consumption of the galvanized coating or the Corten steel core, enabling timely maintenance interventions before the mechanical stability of the solar tracker is fatally compromised.

4.3.2. Soil corrosivity according to ISO 12501 and ISO 9223

The accurate prediction of structural degradation in an agrivoltaic plant requires a dual approach, analyzing both the subterranean and the atmospheric environments. While the German DIN 50929-3 standard provides an exhaustive, multi-factorial framework for soil corrosivity, the European baseline for evaluating the likelihood of corrosion in buried structures is dictated by the standard ISO 12501-2 [63]. For the above-ground superstructure exposed to the open air, the standard ISO 9223 governs the classification and estimation of atmospheric corrosivity [38]. The integration of these two normative frameworks, adapted to the specific operational reality of the agrivoltaic sector, forms the foundation for reliable durability assessments.

Evaluation of soil corrosivity according to ISO 12501-2

The standard ISO 12501-2 is specifically designed for the protection of metallic materials against corrosion, focusing on the corrosion likelihood in soil for low-alloyed and non-alloyed ferrous materials [63]. This specification means that the standard perfectly models the underground behaviour of carbon steel and weathering steel, commonly known as Corten. As previously established, Corten cannot develop its protective oxyhydroxide patina when buried in moist, un-aerated soil, thus behaving similarly to standard carbon steel. Although the standard is primarily tailored for ferrous materials, the fundamental soil parameters it evaluates are directly responsible for the degradation of hot-dip galvanized coatings, making the normative criteria highly relevant for assessing the survival of the protective zinc layer.

Unlike the complex ten-parameter system of the DIN standard, ISO 12501-2 adopts a more streamlined bivariate matrix approach. It primarily classifies the corrosion load based on the intersection of two critical physico-chemical measurements: the pH value

and the electrical resistivity of the soil. The standard establishes three broad classes of corrosion load: low, medium, and high probability that the corrosion rate will exceed a critical threshold or that localized damage will occur [64].

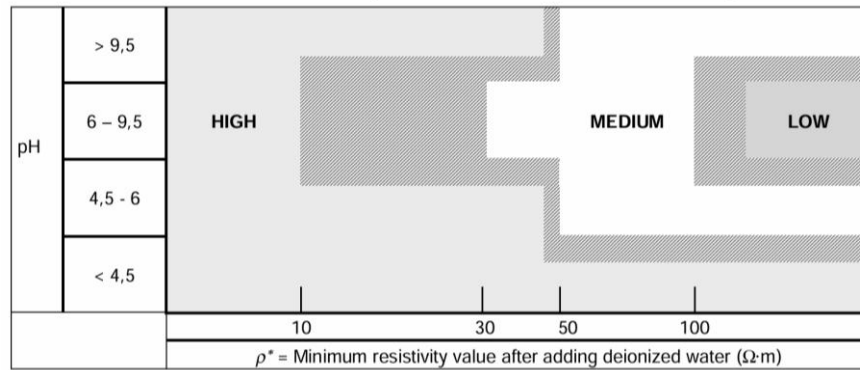


Figure 11 - Corrosion load (free corrosion without cell) [EN 12501-2:2003 table 2]

The pH value measures the hydrogen ion concentration in the soil water extract. According to the standard's classification table, the safest range for ferrous materials lies between a pH of 6 and 9.5 [63]. Within this slightly acidic to slightly alkaline window, carbon steel can form semi-protective iron oxides, and zinc exhibits its minimum solubility due to the stability of basic zinc carbonates. However, conditions leading to a higher risk factor are clearly delineated. If the pH drops below 4.5, the environment is classified unconditionally as having a high corrosion load, regardless of the resistivity. In such highly acidic environments, the protective oxides on Corten steel dissolve and the cathodic evolution of hydrogen gas forcefully accelerates the anodic dissolution of iron. For galvanized steel, the risk is even more acute; zinc, being an amphoteric metal, is rapidly stripped away in acidic conditions. In agrivoltaic contexts, this high-risk acidic condition is frequently artificially induced by the nitrification of ammonium-based fertilizers.

The second primary metric is the electrical resistivity, which indicates the soil's resistance to the flow of galvanic corrosion currents. High resistivity impedes the electrochemical circuit. The standard dictates that soils with a resistivity value below 30 Ω·m are automatically considered locations of high corrosion load [63]. Conversely, a low corrosion load is only assumed if the resistivity is strictly above 100 Ω·m, the soil is composed of sand or gravel, and there are no other negative soil conditions present. In an active agricultural field, the constant application of water through irrigation combined with soluble fertilizer salts drastically lowers the electrical resistivity, frequently pushing the environment from a naturally medium or low risk category into a high corrosion load classification.

The standard also heavily penalizes specific environmental circumstances that act as major risk multipliers. The presence of peat, marshlands, a fluctuating water table, or contamination by fertilizers and manure immediately escalates the predicted corrosion

load to high [63]. Furthermore, if the soil is heterogeneous, generating a wide range of resistivity values or pH values across the length of the driven pile, the formation of macroscopic concentration cells is highly probable, requiring the baseline medium load to be upgraded to high.

Field measurement ratio indicated by ISO 12501-2

The standard ISO 12501-2 mandates specific laboratory procedures for acquiring the classification parameters. For resistivity, the norm requires determining the minimum resistivity value by placing a dried, sieved soil sample into a standardized measurement box equipped with plate electrodes and repeatedly adding known volumes of deionized water until the resistance value reaches its absolute minimum before rising again [63]. Similarly, the pH must be measured using a 1:2 volumetric ratio of soil to liquid.

The critical role of the specialized geologist

The structural failure of an agrivoltaic plant is rarely caused by a sudden mechanical overload; it is almost universally the result of progressive, unmonitored electrochemical degradation. Despite this reality, the standard industrial practice for the preliminary engineering of solar parks relies almost exclusively on mechanical testing.

This approach is fundamentally flawed. As explicitly dictated by ISO 12501-2, the assessment of the corrosion load must begin with a preliminary inquiry and a rigorous site survey, including in-situ resistivity profiling and soil sampling [63]. This comprehensive physico-chemical analysis must be conducted at the very beginning of the construction phase by a specialized geologist. It is imperative that this chemical investigation is integrated seamlessly with the standard mechanical tests, such as pull-out tests, seismic wave analysis, and penetrometric evaluations.

When a geologist performs a pull-out test to determine the skin friction and bearing capacity of the test pile, the corresponding test pit provides the perfect opportunity to extract undisturbed soil samples from the exact stratigraphy where the final structure will reside. Assessing the mechanical holding power of a gravel layer is useless if the chemical analysis reveals that the same layer is highly acidic and saturated with chlorides, which would sever the pile through pitting corrosion within a decade. By integrating the ISO 12501-2 chemical profiling into the preliminary geotechnical campaign, engineers can correctly specify the required galvanization thickness, justify the use of advanced zinc-magnesium alloys, or mandate the application of protective bituminous sheaths before the procurement and installation phases commence.

Atmospheric corrosivity classification according to ISO 9223

Once the steel profile emerges from the soil, it enters a completely different corrosive environment governed by the atmosphere. The standard ISO 9223 establishes a

rigorous classification system for the corrosivity of atmospheric environments, categorizing them from C1 for very low corrosivity up to CX for extreme conditions [38].

Table 6 - Corrosion rates, r_{corr} , for the first year of exposure for the different corrosivity categories [extracted from ISO 9223:2012, Table 2]

Corrosivity category	Corrosion rates of metals				
	Unit	Carbon steel	Zinc	Copper	Aluminium
C1	$\text{g}/(\text{m}^2\cdot\text{a})$	$r_{\text{corr}} \leq 10$	$r_{\text{corr}} \leq 0,7$	$r_{\text{corr}} \leq 0,9$	negligible
	$\mu\text{m}/\text{a}$	$r_{\text{corr}} \leq 1,3$	$r_{\text{corr}} \leq 0,1$	$r_{\text{corr}} \leq 0,1$	—
C2	$\text{g}/(\text{m}^2\cdot\text{a})$	$10 < r_{\text{corr}} \leq 200$	$0,7 < r_{\text{corr}} \leq 5$	$0,9 < r_{\text{corr}} \leq 5$	$r_{\text{corr}} \leq 0,6$
	$\mu\text{m}/\text{a}$	$1,3 < r_{\text{corr}} \leq 25$	$0,1 < r_{\text{corr}} \leq 0,7$	$0,1 < r_{\text{corr}} \leq 0,6$	—
C3	$\text{g}/(\text{m}^2\cdot\text{a})$	$200 < r_{\text{corr}} \leq 400$	$5 < r_{\text{corr}} \leq 15$	$5 < r_{\text{corr}} \leq 12$	$0,6 < r_{\text{corr}} \leq 2$
	$\mu\text{m}/\text{a}$	$25 < r_{\text{corr}} \leq 50$	$0,7 < r_{\text{corr}} \leq 2,1$	$0,6 < r_{\text{corr}} \leq 1,3$	—
C4	$\text{g}/(\text{m}^2\cdot\text{a})$	$400 < r_{\text{corr}} \leq 650$	$15 < r_{\text{corr}} \leq 30$	$12 < r_{\text{corr}} \leq 25$	$2 < r_{\text{corr}} \leq 5$
	$\mu\text{m}/\text{a}$	$50 < r_{\text{corr}} \leq 80$	$2,1 < r_{\text{corr}} \leq 4,2$	$1,3 < r_{\text{corr}} \leq 2,8$	—
C5	$\text{g}/(\text{m}^2\cdot\text{a})$	$650 < r_{\text{corr}} \leq 1\,500$	$30 < r_{\text{corr}} \leq 60$	$25 < r_{\text{corr}} \leq 50$	$5 < r_{\text{corr}} \leq 10$
	$\mu\text{m}/\text{a}$	$80 < r_{\text{corr}} \leq 200$	$4,2 < r_{\text{corr}} \leq 8,4$	$2,8 < r_{\text{corr}} \leq 5,6$	—
CX	$\text{g}/(\text{m}^2\cdot\text{a})$	$1\,500 < r_{\text{corr}} \leq 5\,500$	$60 < r_{\text{corr}} \leq 180$	$50 < r_{\text{corr}} \leq 90$	$r_{\text{corr}} > 10$
	$\mu\text{m}/\text{a}$	$200 < r_{\text{corr}} \leq 700$	$8,4 < r_{\text{corr}} \leq 25$	$5,6 < r_{\text{corr}} \leq 10$	—

NOTE 1 The classification criterion is based on the methods of determination of corrosion rates of standard specimens for the evaluation of corrosivity (see [ISO 9226](#)).

NOTE 2 The corrosion rates, expressed in grams per square metre per year [$\text{g}/(\text{m}^2\cdot\text{a})$], are recalculated in micrometres per year ($\mu\text{m}/\text{a}$) and rounded.

NOTE 3 The standard metallic materials are characterized in [ISO 9226](#).

NOTE 4 Aluminium experiences uniform and localized corrosion. The corrosion rates shown in this table are calculated as uniform corrosion. Maximum pit depth or number of pits can be a better indicator of potential damage. It depends on the final application. Uniform corrosion and localized corrosion cannot be evaluated after the first year of exposure due to passivation effects and decreasing corrosion rates.

NOTE 5 Corrosion rates exceeding the upper limits in category C5 are considered extreme. Corrosivity category CX refers to specific marine and marine/industrial environments (see Annex C).

The standard provides two distinct pathways for determining the corrosivity category: a direct determination based on the actual first-year mass loss of standard metal specimens exposed on-site, and a normative estimation based on calculated first-year corrosion losses using specific dose-response functions. Given that agrivoltaic projects rarely have the luxury of a one-year preliminary exposure campaign, the normative estimation using environmental data is the standard engineering approach.

The dose-response functions provided by the standard calculate the corrosion rate as a complex, non-linear interaction of four fundamental environmental parameters: the annual average temperature, the annual average relative humidity, the annual average sulfur dioxide deposition rate, and the annual average chloride deposition rate [38]. The time of wetness, which dictates the period during which a microscopic film of electrolyte covers the metal surface, is intrinsically modeled within the temperature and humidity variables.

For carbon steel, which mirrors the atmospheric behaviour of unalloyed Corten steel before the patina stabilizes, the dose-response function calculates the first-year

corrosion rate by elevating the sulfur dioxide and chloride deposition rates to specific power exponents, modified by exponential functions containing the relative humidity and a temperature-dependent factor. The equation demonstrates that carbon steel is highly sensitive to both sulfur dioxide and humidity.

For carbon steel:

$$r_{corr} = 1.77 \cdot P_d^{0.52} \cdot \exp(0.020 \cdot RH + f_{St}) + 0.102 \cdot S_d^{0.62} \cdot \exp(0.033 \cdot RH + 0.040 \cdot T)$$

The temperature correction factor, f_{St} , is defined as follows:

$$f_{St} = 0.150 \cdot (T - 10) \text{ when } T \leq 10 \text{ }^\circ\text{C}; \text{ otherwise } f_{St} = -0.054 \cdot (T - 10)$$

$$N = 128, R^2 = 0.85$$

For zinc, which represents the protective coating of hot-dip galvanized structures, the corresponding dose-response function utilizes different empirical coefficients and exponents. Zinc is particularly sensitive to the initial sulfur dioxide deposition, which disrupts the formation of protective basic zinc carbonates, and to chloride ions, which prevent passivation and keep the metal in an active state of dissolution.

For zinc:

$$r_{corr} = 0.0129 \cdot P_d^{0.44} \cdot \exp(0.046 \cdot RH + f_{Zn}) + 0.0175 \cdot S_d^{0.57} \exp(0.008 \cdot RH + 0.085 \cdot T)$$

The temperature correction factor, f_{Zn} , is defined as follows:

$$f_{Zn} = 0.038 \cdot (T - 10) \text{ when } T \leq 10 \text{ }^\circ\text{C}; \text{ otherwise } f_{Zn} = -0.071 \cdot (T - 10)$$

$$N = 114, R^2 = 0.78$$

Where:

- r_{corr} is the first-year corrosion rate of the metal, expressed in micrometres per year ($\mu\text{m/a}$).
- T : is the annual average temperature, expressed in degrees Celsius ($^\circ\text{C}$).
- RH : is the annual average relative humidity, expressed as a percentage.
- P_d : is the annual average sulfur dioxide deposition (SO_2), expressed in milligrams per square metre per day [$\text{mg}/(\text{m}^2 \cdot \text{d})$].
- S_d : is the annual average chloride (Cl) deposition, expressed in milligrams per square metre per day [$\text{mg}/(\text{m}^2 \cdot \text{d})$].
- f_{St} : is the temperature correction factor, which varies depending on whether the annual average temperature is above or below $10 \text{ }^\circ\text{C}$.
- N : represents the sample size (number of data points) used for the regression analysis, which is 128 for this model.
- R^2 : is the coefficient of determination (0.85), indicating the goodness of fit of the regression model to the experimental data.

Simulation of atmospheric corrosivity in the province of Pavia

To fully comprehend how these formulas position an agrivoltaic plant within the standard corrosivity categories, it is highly instructive to simulate the environmental parameters for a typical installation located in the province of Pavia, situated in the Po Valley region of Italy.

The baseline atmospheric conditions in the Po Valley are characterized by a temperate climate with high ambient moisture. The annual average temperature can be estimated at approximately 13°C. The annual average relative humidity is naturally high, hovering around 75%. However, the agrivoltaic context alters this baseline. The presence of extensive underlying crops, particularly irrigated broad-leaf cultures, generates continuous evapotranspiration. This biological pumping of water vapour into the microclimate beneath the solar panels effectively raises the local relative humidity interacting with the steel structures. For this simulation, an elevated average relative humidity of 80% is assumed.

Regarding pollution, the province of Pavia is technically a rural and agricultural area, but it is deeply embedded within the highly industrialized and densely populated Po Valley basin. Consequently, there is a significant background concentration of sulfur dioxide and nitrogen oxides originating from urban heating, highway traffic and industrial facilities in the broader region. Furthermore, local agricultural activities release substantial amounts of ammonia into the air from livestock manure and nitrogen fertilizers. Given this mixed profile, the sulfur dioxide deposition rate can be reasonably estimated at 12 mg/m² per day, placing it at the upper boundary of a rural atmosphere and the lower boundary of an urban classification according to the standard [38].

For airborne salinity, the province of Pavia is entirely inland, meaning the direct oceanic chloride deposition is negligible. However, in an active agricultural setting, the application of potassium chloride fertilizers, combined with the mechanical suspension of soil dust by tractors during dry periods, introduces a localized source of airborne chlorides. To account for this agricultural dust, a chloride deposition rate of 5 mg/m² per day is simulated.

Applying these simulated parameters to the ISO 9223 dose-response functions yields precise estimates for the first-year degradation.

For unalloyed carbon steel or Corten, the temperature factor is calculated based on the difference between the actual temperature and the 10°C threshold. Inserting the variables into the carbon steel equation, the first term driven by sulfur dioxide and humidity produces a significant material loss, while the second term driven by

chlorides adds a smaller but relevant contribution. The resulting calculated first-year corrosion rate for carbon steel in this simulated Pavia environment is approximately 33.5 μm per year.

To interpret this value, we refer to the classification table in the standard. The category C3, denoting medium corrosivity, is defined by a first-year carbon steel loss ranging between 25 and 50 μm per year [38]. The simulated value of 33.5 μm firmly positions the agrivoltaic atmosphere in the lower-middle tier of the C3 category.

Repeating the calculation for the protective zinc coating utilizes the specific zinc dose-response function. Zinc's response to the elevated humidity and moderate sulfur dioxide is mathematically distinct. Processing the same parameters through the zinc equation yields a calculated first-year corrosion rate of approximately 1.46 μm per year.

According to the standard, the C3 category for zinc is defined by a thickness loss ranging from 0.7 to 2.1 μm per year [38]. The simulated value of 1.46 μm per year falls almost exactly in the dead centre of the C3 interval.

This numerical simulation is fundamentally important for the structural design phase. A standard, non-agricultural solar park located on sterile ground in a rural area would likely exhibit lower humidity and near-zero airborne chlorides, potentially falling into the benign C2 category. However, the simulation proves that the specific operational reality of the agrivoltaic system, with its artificially elevated humidity from crop evapotranspiration and the suspension of chemical agricultural dust, pushes the microclimate solidly into the C3 medium corrosivity category.

These finding mandates specific engineering choices for the superstructure. A standard continuous galvanization layer of 20 μm might deplete significantly within the 30-year design life under these precise C3 conditions, especially on cut edges. To guarantee long-term structural integrity and prevent the onset of red rust on the above-ground framework in the Po Valley agrivoltaic context, designers must specify thicker coating (e.g. Z450 use in Vercelli site with a thickness of 33 μm) or heavier hot-dip galvanized coatings compliant with ISO 1461, or transition to advanced zinc-aluminium-magnesium alloys that drastically lower the annual corrosion rate within the same environmental parameters.

4.3.3. Sampling procedures

The reliability of any corrosion assessment depends fundamentally on the integrity of the soil sampling process. The physical and chemical parameters of the telluric environment are highly sensitive to spatial variations, depth, and exposure to atmospheric conditions. Therefore, a rigorous and standardized sampling procedure was developed and executed to ensure that the data collected accurately reflected the actual corrosive environment interacting with the agrivoltaic foundations. This section

details the methodology employed for sample extraction, field measurements, laboratory analysis, the comparison with international standards, and the specific calibration procedures of the instrumentation used.

Extraction and direct spatial correlation

To acquire the soil samples necessary for the physico-chemical analysis, the extraction was performed directly from the inspection pits previously excavated for the visual and ultrasonic assessment of the piles. The samples were taken exactly at the depth of the maximum excavation, typically near 30 cm below the ground level, which corresponds to the air-soil transition zone.

This specific sampling location was not chosen arbitrarily. In the context of agrivoltaic systems, the soil is continuously manipulated by agricultural practices, leading to a highly heterogeneous distribution of moisture, organic matter and fertilizer salts [58]. By extracting the soil from the exact interface where the structural degradation was visually and instrumentally assessed, it was possible to establish a direct spatial correlation between the chemical aggressiveness of the surrounding medium and the localized corrosion effect on the steel profile. This approach eliminates the random spatial variations that would occur if the soil were sampled several meters away from the structure, ensuring that the measured parameters represent the actual electrolyte acting on the specific differential aeration cell at that precise location.

Once extracted using clean tools, the soil specimens were immediately transferred into food-grade plastic bags. These bags were hermetically sealed directly on-site. This immediate sealing is a critical step in geotechnical and geochemical sampling protocols. It serves two primary purposes: firstly, it prevents the evaporation of the natural in-situ moisture, which is essential for understanding the actual water content interacting with the pile; secondly, it prevents external contamination and completely isolates the sample from atmospheric carbon dioxide, which could dissolve into the soil moisture to form carbonic acid, thereby artificially lowering the natural pH of the soil prior to testing.

Normative standards versus the adopted methodology

When evaluating soil corrosivity, the European standard ISO 12501-2 and the German standard DIN 50929-3 provide the primary theoretical frameworks [46]. However, the laboratory procedures dictated by these standards, and by the associated ISO norms, often conflict with the practical necessities of assessing the active, real-time corrosive state of an agricultural field.

According to the rigorous procedures of ISO 12501-2 for determining the specific electrical resistivity, the soil sample must be completely dried in an oven, crushed, sieved to remove large aggregates, and then placed into a standardized measurement container known as a soil box. Distilled water is then added in precise, incremental volumetric steps. After each addition, the electrical resistance is measured until it

reaches its absolute minimum value before beginning to rise again due to over-dilution [63].

Furthermore, for the specific determination of pH and electrical conductivity, international testing norms provide distinct directives. The standard ISO 10390 [65], which governs the determination of pH in soils, explicitly requires a volumetric extraction ratio. It dictates that the soil must be mixed with distilled water in a 1:5 volume fraction. Conversely, the standard ISO 11265 [66], which defines the measurement of specific electrical conductivity in soils, mandates a mass-to-volume ratio, typically prescribing a 1:5 mass ratio (e.g., 20 grams of dried soil to 100 mL of water).

While the standard soil box method and the strict drying protocols of the ISO norms are unquestionable for determining the absolute theoretical minimum resistivity during a preliminary site design phase, they present significant limitations for monitoring active degradation. Drying the soil destroys its actual in-situ chemical state, altering the natural equilibrium of the dissolved agricultural salts and precipitating compounds that might not easily redissolve.

Therefore, for the purposes of this experimental campaign, a customized methodology was applied. The samples were not desiccated; instead, the soil was utilized exactly as extracted from the field, preserving its natural field-moist condition. During the experimental campaign supporting this research, these parameters were measured directly in the field or in a simplified laboratory setup using a portable multiparameter probe. The electrical conductivity and pH was measured utilizing a 1:1 volume ratio of soil to demineralized water. The measured electrical conductivity, expressed in $\mu\text{S}/\text{cm}$, was then mathematically inverted to obtain the specific electrical resistivity.

While this method represents an approximation compared to the rigorous minimum resistivity test defined in the standard soil box, it is a highly valid and necessary simplification for practical engineering and maintenance purposes. The total volumetric dilution ratio of approximately 1:1 is achieved through a two-step process. First, demineralized water is added to the soil sample at its natural moisture concentration until complete saturation is reached—defined as the exact point where all water is absorbed and any further addition would create free water on the surface. This state simulates the worst-case operative scenario in the field. Subsequently, an additional 0.5 volume of water (relative to the saturated mixture) is added. This specific fraction accounts for the soil's average 50% volumetric water absorption capacity while providing the minimum amount of free liquid necessary to safely operate the measuring probe without damaging it. This approach effectively dissolves all soluble salts into the aqueous phase without significantly altering the concentration, yielding measurements that remain highly comparable to the values prescribed by the normative standards. Because the fundamental goal of the field inspection is to identify sudden spikes in soil aggressiveness caused by farming

practices, this approximation captures the maximum ionic load available for galvanic conduction. It provides a conservative baseline that prevents the underestimation of the corrosion risk. Most importantly, it allows maintenance technicians to perform rapid, reliable and repeatable periodic checks on-site without requiring access to a fully equipped geotechnical laboratory.

Field measurement: oxidation-reduction potential

Certain soil parameters are extremely volatile and must be measured immediately upon extraction to yield valid results. The oxidation-reduction potential is the most critical of these. The potential indicates the degree of aeration of the soil; a positive value indicates an oxidizing environment, while a negative value indicates a reducing, anoxic environment conducive to the proliferation of anaerobic sulfate-reducing bacteria. If a sample taken from a deep, damp layer is exposed to the atmosphere, oxygen rapidly diffuses into the soil matrix, artificially raising the redox potential and entirely masking the true anaerobic corrosion risk.

For this reason, the measurement was conducted directly in the field, utilizing the soil freshly extracted from the 30 cm depth to minimize atmospheric oxygenation. The measurement was performed using the Apera ORP60 portable tester.

The preparation of the sample for the field reading utilized a standardized 1:1 volumetric ratio. Calibrated plastic cups were employed as measurement vessels. The cup was filled with the extracted soil up to a pre-marked line representing one-third of its total height, yielding a sample volume of approximately 50 mL. An exactly equal volume of demineralized water (filling another one-third of the cup) was then added. The use of plastic cups and a plastic stirring stick is a fundamental methodological precaution; utilizing any metallic tools or metallic containers would introduce stray galvanic currents and external metal ions into the solution, which would immediately corrupt the sensitive electrochemical reading. After thoroughly mixing the soil and water with the plastic stick, the suspension was left to decant briefly (only 30 - 90 s).

The calibration and preparation of the Apera ORP60 instrument were performed strictly according to the manufacturer's operational guidelines [67]. The platinum measurement electrode of an oxidation-reduction probe must be maintained in a highly active state to ensure rapid and accurate electron exchange. Prior to the field measurements, the probe was conditioned by soaking it in a 3M potassium chloride storage solution for at least one hour. Before taking the actual reading, the instrument was calibrated using a standard reference liquid providing a known, stable potential of 222 mV. Once verified, the probe was inserted into the decanted soil suspension, ensuring the platinum pin was fully submerged but not forcefully driven into the solid sediment. The value was recorded once the digital reading stabilized. The instrument features a built-in temperature sensor that automatically compensates the reading, which is crucial for field operations where ambient temperatures fluctuate. Between

each sample, the measuring head was thoroughly rinsed with demineralized water from a portable squeeze bottle and gently blotted dry to prevent cross-contamination between different test pits.

Laboratory measurement: pH and electrical conductivity

The measurement of the hydrogen ion concentration and the electrical conductivity was conducted on the sealed samples in a controlled laboratory environment. Operating in a laboratory ensures a stable ambient temperature of approximately 21 °C. Temperature stability is crucial because both conductivity and pH are highly temperature-dependent properties; avoiding the extreme temperature fluctuations typical of an open agricultural field minimizes the algorithmic compensation errors of the measurement probes.

These analyses were performed using the Apera PC60-Z multiparameter smart tester. For these specific parameters, the preparation of the aqueous extract followed the theoretical principles outlined by the reference standards, adapted for the field-moist soil. For the determination of the pH and electrical conductivity is used 1:1 ration described before.

Prior to commencing the laboratory readings, the Apera PC60-Z was subjected to a rigorous multipoint calibration process, following the manufacturer's specifications [55]. For the pH sensor, standard buffer solutions at pH 4.00 and pH 7.00 were utilized. This specific acidic-to-neutral range was deliberately chosen because agricultural soils subjected to intensive fertigation typically exhibit properties within this window; calibrating across this specific span maximizes the instrument's linearity and accuracy for the expected values. For the conductivity sensor, standard calibration solutions at 1413 $\mu\text{S}/\text{cm}$ and 12.88 mS/cm were employed to ensure accurate detection across the wide range of salinities potentially caused by fertilizer accumulation.

Once the soil and demineralized water mixtures were prepared in plastic containers, they were vigorously stirred with a plastic stick and allowed to decant. Decantation is a vital mechanical step; inserting the highly sensitive, ultra-thin glass bulb of the pH electrode directly into a harsh mixture of suspended sand and agricultural gravel could easily scratch the membrane or clog the porous reference junction, leading to sluggish, erratic, or permanently damaged readings. The combined measuring head of the PC60-Z was carefully immersed into the clear supernatant liquid situated above the settled soil particles. After the value stabilized on the digital display, the probe was extracted, thoroughly rinsed with a continuous stream of pure demineralized water to remove any residual dissolved agricultural salts or microscopic clay particles, and prepared for the subsequent sample analysis.

5 Chapter 5: experimental results

5.1. Site characterization of investigated plants

The transition from theoretical models of soil and atmospheric characteristics to the practical evaluation of structural configurations requires a rigorous and extensive field investigation. The experimental campaign supporting this research was conducted entirely during the months of January and February 2026. This specific temporal window is of fundamental importance for geotechnical and agronomic assessments across the investigated European geographical contexts. During the winter season, agricultural soils typically reach their maximum water saturation levels, and the groundwater table rises to its seasonal peak. These environmental conditions represent a critical baseline scenario for understanding the operational environment of buried metallic structures. The field campaign encompassed a total of nine distinct photovoltaic and agrivoltaic installations, carefully selected to provide a comprehensive overview of the different variables influencing solar infrastructure.

The chosen sites present a wide heterogeneity in terms of geographical location, altitude, proximity to the sea, operational age, specific structural materials, coating thicknesses, foundation typologies, and agricultural integration. This section provides a detailed and exhaustive technical characterization of all the investigated plants. The descriptions establish the specific environmental and structural baselines based exclusively on the data collected directly in the field, the environmental context of the localities, and the technical documentation made available by the respective plant operators.

Plant 1: province of Modena (MO)

Focusing on the first installation, this plant is a recently constructed agrivoltaic system located in the province of Modena, situated in the province of Modena, within the Emilia-Romagna region. Geographically, Modena lies in the heart of the Po Valley at a very low altitude. This inland location is far from the sea, meaning it is entirely uninfluenced by maritime salinity, but it is characterized by a typical continental climate with hot, humid summers and cold, damp winters with frequent fog. The property is owned and managed by GSC, a specialized company that develops renewable energy plants. Notably, this specific installation was developed as part of the national agrivoltaic funding program, reflecting a modern approach to integrated land use.



Figure 12 - Plant of Modena

The plant features an installed peak power capacity of 1940.3 kW and utilizes a fixed mounting structure. The construction phase, with specific reference to the placement of the foundation piles, was officially completed on April 1, 2025. The structural design distinguishes itself by relying entirely on unalloyed weathering steel. Specifically, Corten grade S355 was chosen for the heavily stressed vertical foundation piles, while Corten grade S235 was utilized for the lighter above-ground upper structure. The entire assembly is mechanically connected using high-grade class A2-70 stainless steel bolts. The vertical foundation supports consist of open C-shaped profiles. The geometric dimensions of this cross-section feature a primary main side of 160 mm, a width of 80 mm, and structural lips of 25 mm, maintaining a uniform material thickness of 2.5 mm throughout the profile length.

The foundations were realized by direct mechanical pile ramming into the native soil without the use of concrete. During the winter field visit, the hydrogeological conditions were observed to be particularly saturated. The groundwater table was situated precisely at ground level, creating a thoroughly muddy environment with frequent and extensive water stagnation. A highly specific observation was the presence of a continuous perimeter ring of water, approximately 1 cm wide, surrounding the driven pile and extending downwards into the soil profile to a verified depth of 70 cm during the winter season, an interface that completely dries out during the summer. At the time of the inspection, the terrain beneath the solar panels remained uncultivated, as the final agricultural layout and the specific crop selection are still being actively defined in consultation with an agronomist.

Regarding the technical documentation, the structural engineering report was made available for review. An analysis of the calculations revealed that no extra sacrificial metal thickness was planned for the Corten steel beyond its nominal structural requirements. Furthermore, the site lacks a preliminary chemical analysis of the soil,

as only mechanical penetrometric tests and multichannel analysis of surface waves were performed prior to construction to assess the bearing capacity. The provided maintenance plan is exceedingly brief, consisting of only half a page that merely requires an annual visual verification without specifying any deeper instrumental checks. To monitor the local microclimate, a meteorological station is installed on-site, configured to record both air and soil humidity and temperature, although its historical data logging only dates back to October 2025, a timeframe that is currently insufficient for establishing a complete annual climatic average for corrosion estimation.

Plant 2: province of Vercelli (VC)

The second installation is a massive traditional photovoltaic plant situated in the province of Vercelli, in the province of Vercelli, Piedmont. This geographical area is located at an altitude of approximately 200 m above sea level and is historically renowned for its extensive flooded rice paddies. The climate is continental and notoriously humid, heavily influenced by the dense network of agricultural irrigation canals, while remaining completely isolated from any marine influence. The plant is managed by Repower, a major international energy utility company managing significant renewable assets. The system boasts a highly significant installed peak power, totaling 19530 kW of panel capacity, and employs an advanced single-axis tracking structure to optimize solar yield.



Figure 13 - Plant of Vercelli

The foundation piles were installed recently on August 1, 2025. The structural materials chosen for this site reflect a heavy-duty approach, consisting entirely of highly specified protected steel. The vertical foundation piles are manufactured from

hot-dip galvanized steel, utilizing high-strength grade S420J2 or grade S355J2, with an average measured zinc coating of 90 μm . These foundation supports feature robust C-shaped profiles with a main side length of 180 mm and a substantial thickness of either 3 or 4 mm depending on the specific mechanical loads. The upper moving structure is composed of pre-galvanized octagonal tubes made of S420GD J2 steel featuring a continuous Z450 coating, with dimensions of 143.7 by 2.3 mm. This is complemented by pre-galvanized Ω profiles in S450GD steel, also with a Z450 coating, measuring 21.5 x 60 x 30 x 2.2 mm.

The foundations are formed by cylindrical concrete plinths with a diameter of 500 mm. A critical design choice observed during construction was that these plinths terminated approximately 10 cm below the natural subsoil level. The local hydrogeological conditions are characterized by a groundwater table sitting exactly at ground level, which, combined with the uncultivated gravelly terrain originating from a former quarry, causes significant mud and water stagnation. Complete technical documentation was available for this site, including both the structural engineering report and a comprehensive chemical soil analysis executed according to the rigorous DIN 50929 standard. During the winter inspection, evident water stagnation was observed exactly at the interface between the galvanized steel pile and the sunken concrete plinth, a condition that disappears during the dry summer months. To properly manage this geometric vulnerability, an estimative evaluation was formally requested by the operators to support the immediate correction of the plinths during the active construction phase, specifically aiming to raise the concrete casting above ground level with a 20 cm collar and a draft angle to favor proper water drainage.

Plant 3: Pavia (PV)

Located directly within the university campus, this specific photovoltaic system serves a dual architectural purpose, acting as an elevated canopy structure designed to provide coverage for a large vehicular parking lot. The plant is situated in Pavia, in the Lombardy region, an area located in the lower Po Valley. The climate here is strictly continental, characterized by hot summers and cold winters with highly persistent periods of dense fog and elevated atmospheric humidity, remaining thoroughly isolated from any coastal dynamics. The property is formally under the University of Pavia, an academic institution, although its historical operational management and maintenance are handled by the energy company Unienergy srl.



Figure 14 - Plant of Pavia

The plant has an installed peak power capacity of 1179 kW and was constructed historically around January 1, 2013. The system features a fixed structural layout completely manufactured from hot-dip galvanized steel. Although the exact original steel composition is not specifically documented in the available historical records, engineering standards of the time suggest it is presumed to be structural grade S235 or S275. The primary vertical columns have a large circular hollow section with an external diameter of 180 mm. Field estimation indicated that the hot-dip galvanization applied has a starting average thickness of approximately 90 μm .

The foundations display a notable architectural variation across the site. Depending on the specific column observed, the foundation consists either of a deep concrete block driven directly into the soil, or a concrete base entirely covered by a superficial decorative layer of crushed gravel, while a few remaining plinths are covered by standard soil. The groundwater table is not visually detectable from the surface and is estimated to be relatively shallow, at a depth of roughly 1 m. There is no agricultural vegetation integrated into this site, as the area serves entirely as an uncultivated, paved, and gravel parking surface. Access to the historical construction records, original geochemical surveys, and material certificates was unfortunately not possible, as this technical documentation remains completely inaccessible due to the long-standing management and ownership arrangements established with the utility provider over the years.

Plant 4: province of Rovigo (RO)

This massive photovoltaic installation is located in the province of Rovigo, within the Veneto region. Geographically, this area is situated in the eastern expanse of the Po Valley. While relatively closer to the Adriatic Sea compared to the previous western sites, the atmosphere is primarily continental and highly humid agricultural, typical of the flatland farming districts. The site is managed by the energy utility Repower.



Figure 15 - Plant of Rovigo

The original construction of the foundations and support structures dates back to January 1, 2013. Originally featuring an installed peak power of 5650 kW, the plant underwent a massive repowering process in 2021. This substantial technical intervention included the complete replacement of the photovoltaic panels, increasing the total installed peak power to an impressive 7440 kW. This structural repowering implies a clear operational intention by the utility company to extend the functional use of the existing metallic support framework far into the future, significantly beyond its original depreciation schedule.

The system relies on complex dual-axis solar trackers constructed entirely from hot-dip galvanized steel, utilizing the common structural grade S235JR. Field estimation conducted on the structural elements indicate at least an average heavy zinc coating thickness of 90 μm . The primary vertical foundation columns consist of highly robust circular hollow profiles with an external diameter of 355.6 mm and a massive material thickness of 5.6 mm. These massive columns were installed into the ground via specialized vibro-ramming techniques. The groundwater table is not visible from the surface but is estimated to be situated at a depth of approximately 1 m. As one of the earliest examples of genuine agrivoltaic integration, the vast terrain beneath the tracking panels is actively utilized for diverse agricultural crop rotations, seamlessly integrating the solar hardware with the cultivation of wheat, soy, protein peas, and rapeseed. Tillage operations in this field are deliberately kept to a minimal depth, restricted to a maximum of 30 cm, due to the presence of underground electrical cables crossing the agricultural surface. A thorough review of the original construction report from 2013 confirmed the structural details, but it was noted that no geochemical analysis of the soil was executed prior to the plant's installation.

Plant 5: Castelvetro (PC)

The fifth installation is an advanced agrivoltaic site situated in Castelvetro, in the province of Piacenza, Emilia-Romagna. Located in the Po Valley, the site experiences a classic continental climate with significant thermal excursions and high humidity, physically isolated from any marine weather patterns. The plant is operated by Remtec, a specialized company that produces and holds international patents on its uniquely designed elevated mounting structures, while also actively utilizing the site to conduct dedicated agronomic research and development.



Figure 16 - Plant of Castelvetro [68]

Constructed on January 1, 2011, the plant features an installed peak power of 1293.6 kW utilizing a highly elevated dual-axis solar tracking architecture. The structural framework relies on a specialized multi-layer component system. This consists of an initial hot-dip galvanization layer, presenting an average measured thickness of 90 μm , which is further completely enveloped by an industrial paint layer. The specific layers and paint composition remains strictly undocumented. The main vertical columns feature a standard circular hollow section with an external diameter of 200 mm.

The foundations are realized with poured concrete plinths that are physically raised approximately 10 cm above the surrounding natural ground level. However, they feature a completely flat top surface, creating a highly complex mechanical node at the base. This interface simultaneously integrates a combination of diverse materials, including the concrete matrix itself, the galvanized and painted steel of the primary column, and robust stainless steel tie rods. These tie rods are utilized across the entire field for the dynamic tensioning and overall structural stabilization of the complex, over-engineered tracker framework, creating multiple physical connections between the individual piles. The groundwater table is situated at an estimated depth of 2 m and is not visible from the surface. The agricultural integration is highly active and scientifically monitored, hosting various intensive crop rotations such as maize, wheat,

soy, and tomatoes in direct and continuous collaboration with the Università Cattolica of Piacenza. Due to corporate confidentiality, information regarding the technical engineering reports and any preliminary soil analyses are not given.

Plant 6: Paicenza (PC)

Located directly within the municipality of Piacenza, Emilia-Romagna, this agrivoltaic installation shares the exact same geographical and climatic context as the Castelvetro site, featuring a low-altitude continental environment typical of the central Po Valley. The plant is owned and managed directly by the Università Cattolica, an esteemed academic institution that utilizes the land beneath the solar panels specifically for dedicated agronomic research purposes and controlled crop experimentation. The installation features an installed peak power of 503 kW of modules and utilizes an advanced dual-axis tracking system.



Figure 17 - Plant of Piacenza

The foundation piles were officially constructed on June 1, 2024. The structure utilizes a distinctly different, highly specialized engineering approach compared to the traditional single-pole sites, acting essentially as a structural evolution of the patents developed by Remtec. The framework consists of a complex tubular truss structure entirely manufactured from hot-dip galvanized steel, presenting an average zinc coating thickness of 90 μm across the accessible members. Instead of relying on a single central column or concrete plinths, this system utilizes an anchored foundation consisting of four distinct underground screw piles for each base, each with a diameter of 100 mm, driven deeply down to 4 m into the soil. Above ground, this transitions

into a robust tubular truss framework utilizing profiles with a 60 mm diameter and a 4 mm thickness.

The groundwater table is not visible and is estimated to reside at a depth of roughly 2 m. As a dedicated university research site, the land is subjected to highly specific and closely monitored agronomic rotations designed for scientific study. The actively cultivated crops within the agrivoltaic layout include wheat, forage, soy, with various other experimental varieties scheduled for the future. Due to the complex footing design, no mechanical tillage treatments are performed directly under or around the truss piles; vegetation control in the immediate structural vicinity is managed exclusively through the application of glyphosate herbicide. The specific technical engineering reports were not retrieved, and it was confirmed that no preliminary geochemical analysis was executed prior to installation.

Plant 7: Ora (BZ)

Situated in the municipality of Ora, within the province of Bolzano in the Trentino-Alto Adige region, the seventh agrivoltaic installation presents a radically different environmental context. Located in an alpine valley, the site is deeply embedded within a mountainous geographical setting. The climate is strictly alpine-continental, characterized by extremely significant thermal excursions between day and night and between the winter and summer seasons.



Figure 18 - Plant of Ora

This installation is operated by Eurac Research, a prominent research center, acting under the umbrella of the European Symbiosist project. It is a highly specialized, small-scale installation with an installed peak power of 72.4 kW. The foundation piles were

recently driven into the soil on May 1, 2025, to support a single-axis tracking system tailored for deep orchard integration. The structural design is particularly notable for featuring a deliberate bimetallic combination. The foundation piles directly rammed into the soil are made of hot-dip galvanized steel presenting an average zinc thickness of 90 μm . In stark contrast, the aerial portion of the main piles exposed to the atmosphere, as well as the entirety of the upper supporting structure, are manufactured from unalloyed Corten weathering steel, utilizing structural grades S355 (piles) and S235 (upper structure) respectively. The main vertical supports utilize an Ω -shaped profile with a main side dimension of 210 mm and a robust material thickness of 5 mm.

The groundwater table is not visible from the surface and is estimated to be approximately 1 m deep. The plant is beautifully integrated into an active, fully mature orchard, specifically covering apple trees of the Ipador variety. The agricultural layout is strictly organized with a precise North-South orientation, cultivated using a Guyot training system where the plant canopy reaches a considerable height of 3 to 3.5 m, with a strictly controlled inter-row spacing of 2.5 m. Because of this existing canopy, the overall solar structure is exceptionally elevated, towering at 4.8 m above ground. The foundation piles were rammed directly into the soil while carefully respecting the original inter-row spacing of the existing fruit plants. Agricultural treatments within this site are subjected to strict regulatory control, managed directly by the agronomists of the Laimburg, ensuring detailed reporting for the European funding framework. No construction documents or geochemical soil analyses were retrieved for this specific site.

Plant 8: Almeria (Spain)

The eighth investigated site introduces an international dimension to the experimental campaign. Located in Almeria, within the autonomous community of Andalusia in southern Spain, this installation is situated in a coastal Mediterranean environment. The geography dictates a semi-arid, almost desert-like coastal climate, characterized by very low annual precipitation, extremely high solar irradiation, and a high degree of atmospheric salinity due to its immediate proximity to the Mediterranean Sea. The plant is an experimental agrivoltaic installation managed by the German Aerospace Center, a major research institution commonly referred to by its acronym DLR.



Figure 19 - Plant of Almeria [69]

It is a highly specialized, small-scale system with a minimal installed peak power of 10.8 kW, utilizing a fixed mounting framework whose structural supports were installed on January 1, 2025. The entire supporting structure is manufactured exclusively from hot-dip galvanized steel, featuring an average zinc coating thickness of 45 μm . The vertical support piles are characterized by a precise square tubular section, with a side length of 75 mm and a relatively thin material thickness of 2 mm. The foundations are realized by directly driving these galvanized square piles into the dry ground by ramming, completely avoiding the use of any concrete plinths. The depth and specific state of the local groundwater table at this location are not visually detectable from the surface and remain entirely unknown.

The agricultural integration at this specific site consists of a specialized organic viticulture operation, meticulously cultivating Merlot grapevines beneath the fixed solar panels. A key operational feature of the site's agronomic management is the heavy and frequent use of elemental sulfur and its chemical derivatives, specifically including various agricultural sulfates and sulfides, which are utilized as targeted fertilizers and organic treatments directly within the crop layout. Due to its nature as an improvised, turnkey experimental prototype commissioned rapidly for specific research purposes, the structure was not built following standard normative codes, resulting in a complete lack of formal technical construction documentation available for review.

Plant 9: Barcelona (Spain)

The final investigated site is also located in Spain, situated in the coastal metropolitan area of Barcelona, Catalonia. This geographical positioning subjects the plant to a classic coastal Mediterranean climate, defined by mild, relatively humid winters and warm, dry summers. Its immediate proximity to the Balearic Sea guarantees a significant and constant maritime influence, loading the local atmosphere with a baseline of marine aerosols. The site is operated as a dedicated research installation under the European Symbiosist project.



Figure 20 - Plant of Barcelona [70]

It is an active agrivoltaic plant with a total installed peak power of 47.2 kW of panels, employing an advanced dynamic single-axis solar tracker specifically configured to maximize light interception while balancing the shading over the crops below. The foundation structure was officially installed into the agricultural soil on January 1, 2025. The entire structural framework is constructed from high-quality hot-dip galvanized steel. Notably, the zinc coating thickness measured at this specific coastal site is highly substantial, averaging an impressive 90 μm , a specification necessary to combat the harsh environment. The structural vertical supports utilize a standard open Ω -shaped profile with a main side length of 210 mm and a robust material thickness of 5 mm, driven directly into the earth by mechanical pile ramming to form the foundations.

The depth of the groundwater table is not visible from the surface and is currently unknown. The solar structure is elevated at a height of 2.8 m above ground level. The site is actively and intensively cultivated to produce a highly varied yield of vegetables, and the specific crop rotation currently growing beneath the tracking panels includes lettuce, fava beans, onions, and tomatoes. Similar to the Ora installation, the agricultural treatments are subject to strict control and oversight, a requirement mandated by the detailed reporting protocols of the European funding program backing the Symbiosist project. While no formal structural engineering documents or geochemical soil data were retrieved from the operators, the site stands out technically because it benefits from an extraordinarily extensive environmental monitoring system. This advanced digital infrastructure continuously records a vast array of precise agronomic and atmospheric parameters, including both air and soil humidity and temperature, precise levels of photosynthetically active radiation,

comprehensive wind speed and directional data, natural rain volume, and the exact volumetric flow of artificial irrigation water applied to the crops.

5.2. Collected parameters for soil corrosivity rating

The evaluation of the electrochemical aggressiveness of the underground environment represents a fundamental step in defining the expected service life of the investigated solar support structures. The data collected during the field campaigns must be systematically processed through the analytical frameworks provided by the international normative standards, specifically the European standard EN 12501-2 and the German standard DIN 50929-3 [46]. Before detailing the numerical results for each specific photovoltaic and agrivoltaic plant, it is necessary to provide a brief methodological introduction regarding the correlation between the field measurement procedures and the strict laboratory dictates of the aforementioned standards.

Table 7 - Experimental results for soil corrosivity rating

Location	Test	Soil structure	pH	EC1:1 [$\mu\text{S}/\text{cm}$]	Ece [$\mu\text{S}/\text{cm}$]	ρ_e [$\Omega\cdot\text{m}$]	pH Mean	ρ_e Mean
Prov. Modena	1.1	Clay	7,72	465	698	14,34	7,70	17,43
	1.2	Clay	7,75	346	519	19,27		
	1.3	Clay	7,64	357	536	18,67		
Prov. Vercelli	2.1	Sand	7,77	550	825	12,12	7,32	26,31
	2.2	Sand	7,65	330	495	20,20		
	2.3	Sand	6,55	143	215	46,62		
Pavia	3.1	Sand	6,00	4300	6450	1,55	6,82	5,95
	3.2	Sand	7,46	15460	23190	0,43		
	3.3	Sand	7,00	420	630	15,87		
Prov. Rovigo	4.1	Clay	7,87	237	356	28,13	7,92	26,27
	4.2	Clay	7,90	280	420	23,81		
	4.3	Clay	8,00	248	372	26,88		
Piacenza	5.1	Clay	7,70	330	495	20,20	7,68	18,62

	5.2	Clay	7,70	390	585	17,09		
	5.3	Clay	7,65	359	539	18,57		
Ora (BZ)	6.1	Sand-silt	7,28	360	540	18,52	7,52	27,68
	6.2	Sand-silt	7,67	137	206	48,66		
	6.3	Sand-silt	7,60	420	630	15,87		



Figure 21 - Test sample at the blistering fase

As described in the methodology, the physico-chemical parameters of the soil, specifically the hydrogen ion concentration and the electrical conductivity, were obtained using a simplified volumetric dilution method. The measured values, particularly the pH, are considered immediately adequate and directly applicable for the assessment matrix defined by the EN 12501-2 standard. However, the German DIN 50929-3 standard relies on a slightly different theoretical baseline for its measurement cells, which theoretically requires a lower degree of water dilution to establish the corresponding acidity. To compensate for this methodological variance, an algorithmic correction is implemented. For all calculations utilizing the DIN 50929-3 tables, the actual pH value utilized for scoring is considered to be 0.1 points lower than the instrumental value recorded in the field.

Furthermore, a comprehensive application of the DIN 50929-3 standard requires the input of several specific chemical parameters, such as the buffer capacity, the exact concentration of neutral salts, and the presence of sulfate-reducing bacteria, which

require complex laboratory titrations not available during rapid field maintenance inspections. To maintain the integrity of the predictive model without artificially inflating the baseline risk, these unmeasured parameters are strictly assumed at realistic, neutral baseline values. For instance, the buffer capacity parameter is universally assigned a neutral value of 0, while neutral salts and sulfides are initially assumed to be below critical thresholds, scoring 0. However, because agrivoltaic soils are actively manipulated, the potential accumulation of agricultural fertilizers allows us to mathematically explore how these baseline ratings could realistically worsen over time. Throughout this chapter, specific electrical resistivity values will be expressed directly in $\Omega\cdot\text{m}$, corresponding to the values recorded in the field dataset.

It must be explicitly noted that three specific sites included in the broader technical analysis are excluded from this numerical geochemical evaluation. These are the advanced Remtec installation in Castelvetro (Piacenza), the Symbiosist project in Barcelona, and the DLR experimental plant in Almeria. The lack of physical soil values for these three locations stems from the fact that they were not visited directly for physical sampling. Instead, the structural and environmental conditions were evaluated through a joint remote and on-site analysis conducted alongside the resident expert researchers working on those specific facilities, who did not have the necessary multiparameter probes and ultrasonic thickness gauges available at their disposal to execute the standardized measurement protocol.

Plant of Province of Modena (MO)

The data extracted from the Modena installation reveals a distinctly challenging telluric environment. The soil structure is predominantly clay, known for its high water retention and poor aeration. The field measurements across three different test pits yielded pH values of 7.72, 7.75, and 7.64, resulting in a mean pH of 7.70. The specific electrical resistivity measurements recorded values of 14.34, 19.27, and 18.67 $\Omega\cdot\text{m}$, providing a mean resistivity of 17.43 $\Omega\cdot\text{m}$.

Because the structural design of this specific plant relies entirely on unalloyed Corten weathering steel, the evaluation according to DIN 50929-3 utilizes the comprehensive total rating for free corrosion, designated as the B_0 index. Applying the realistic mean values to the standard, the heavy clay soil structure incurs a severe Z_1 penalty of -4. The mean resistivity of 17.43 $\Omega\cdot\text{m}$ falls into the 10 to 20 $\Omega\cdot\text{m}$ bracket, incurring a Z_2 deduction of -4. The moisture content, visually verified to be high due to the water table, triggers a Z_3 score of -1. The adjusted mean pH of 7.60 falls in the safe alkaline window, scoring 0 for Z_4 . Assuming neutral realistic values for buffer capacity and chemical contaminants, the algebraic sum provides a baseline B_0 rating of -9, which indicates a medium to high corrosion load [46].

However, this baseline can rapidly deteriorate. If we consider the potential extra penalties typical of an agricultural setting, the introduction of sulfate and chloride-based fertilizers could easily push the neutral salts parameter (Z_9) from 0 down to -2

or -4. This realistic agricultural worsening would drag the total B_0 rating well below the -10 threshold, shifting the classification to highly corrosive and predicting severe pitting rates incompatible with unprotected Corten steel.

A critical feature of the Modena site is the hydrogeological reality where the groundwater table rests precisely at the ground level, effectively submerging the foundation piles. In this scenario, the DIN standard dictates the evaluation of the critical air/water interface using the N parameters for unalloyed steel, culminating in the W_1 rating. The presence of standing water yields a realistic N_1 score of -1, while the location at the water/air interface triggers the N_2 multiplier parameter of 1. With an adjusted pH above 7.5, the N_6 score is +1. Assuming a neutral base for dissolved salts ($N_3=0$), the base W_0 rating equates to 0, leading to a baseline W_1 rating of +1, which suggests very low localized corrosion. However, as an extra consideration, if dissolved agricultural salts accumulate in this stagnant surface water, dropping the N_3 parameter to -2, the W_1 index would plummet, revealing a sudden and high likelihood of intense localized pitting exactly at the waterline.

Transitioning to the EN 12501-2 standard, the evaluation utilizes Table 2. The mean pH of 7.70 places the environment in the central safe bracket. However, the critical deciding factor is the mean resistivity of $17.43 \Omega \cdot m$, which is situated firmly below the $30 \Omega \cdot m$ safety threshold. The intersection of these two parameters automatically categorizes the Modena site as possessing a high corrosion load, perfectly aligning with the potential DIN calculations and confirming the danger to the ferrous material [63].

Plant of Province of Vercelli (VC)

The Vercelli site presents a sandy soil matrix, which traditionally offers better drainage and aeration. The pH readings showed a wider spread, with values of 7.77, 7.65, and a notably lower 6.55, resulting in a mean pH of 7.32. The electrical resistivity values were 12.12, 20.20, and $46.62 \Omega \cdot m$, yielding a mean of $26.31 \Omega \cdot m$.

Because the foundations are manufactured from hot-dip galvanized steel, the DIN 50929-3 assessment shifts to evaluate the protective coating using the B_D rating. Using the realistic mean values, the adjusted pH of 7.22 provides a neutral Z_4 score of 0. The mean resistivity of $26.31 \Omega \cdot m$ falls into the 20 to $50 \Omega \cdot m$ bracket, generating a moderate Z_2 penalty of -2. Assuming neutral baseline values for buffer capacity and microbiological activity (Z_5, Z_6, Z_7 all equal to 0), the resulting baseline B_D rating is -2. This score indicates a good protective capacity of the zinc coating over time.

If we evaluate the site based on the worst single test result to understand local variations, test 2.1 recorded a resistivity of $12.12 \Omega \cdot m$. Applying this specific value drops the Z_2 score to -4, pushing the localized baseline B_D rating to -4. Furthermore, as an extra consideration for the future, if the constant flooded state of the rice paddies encourages the proliferation of sulfate-reducing bacteria, a highly realistic scenario in

anoxic sandy-loams, the Z_7 parameter would introduce an additional -3 penalty, dragging the B_D rating into the inadequate zone.

Similar to Modena, half of the Vercelli plant features a submerged environment due to the high water table. For galvanized steel, this interface is evaluated using the M parameters to calculate the W_L rating. The standing water grants a slightly protective M_1 score of +1. The adjusted pH yields an M_6 score of +1. Assuming neutral salts for the baseline ($M_3=0$), the base W_D rating is +2. However, the exact location at the water/air interface introduces a massive, unavoidable M_2 penalty of -6. The final baseline W_L rating calculates to -4. This specific rating warns that while the deep underwater zinc might survive well, the coating exactly at the waterline is susceptible to a moderate depletion rate [46].

Evaluating Vercelli according to EN 12501-2 Table 2 reveals the importance of spatial analysis. The mean pH of 7.32 and the mean resistivity of $26.31 \Omega \cdot m$ place the general site precisely in the high corrosion load category, as the resistivity sits just below the $30 \Omega \cdot m$ limit. Furthermore, the standard contains a specific clause regarding soil heterogeneity. The wide gap between the maximum resistivity of $46.62 \Omega \cdot m$ and the minimum of $12.12 \Omega \cdot m$ generates a ratio vastly exceeding the acceptable limits, guaranteeing the formation of macroscopic concentration cells and confirming the high corrosion load classification across the entire tracker row [63].

Plant of Pavia (PV)

The data retrieved from the Pavia university parking canopy represents the most extreme electrochemical environment of the entire campaign. The sandy soil exhibited pH values of 6.00, 7.46, and 7.00, with a mean of 6.82. The electrical resistivity values were astonishingly low, recording 1.55, 0.43, and $15.87 \Omega \cdot m$, with a mean of $5.95 \Omega \cdot m$. The value of $0.43 \Omega \cdot m$, corresponding to an electrical conductivity of $23190 \mu S/cm$, is exceptionally severe and strongly implies heavy local contamination, likely from the massive use of de-icing salts during winter maintenance of the parking surface.

Evaluating the hot-dip galvanized columns using the DIN 50929-3 B_D rating produces alarming baseline results. The mean resistivity of $5.95 \Omega \cdot m$ falls into the absolute lowest bracket defined by the standard ($<10 \Omega \cdot m$), triggering the maximum possible Z_2 penalty of -6. With an adjusted mean pH of 6.72 scoring a neutral 0, and maintaining realistic neutral assumptions for unmeasured chemical parameters, the baseline B_D rating is -6. This indicates a satisfactory to inadequate protective capability.

However, if the calculation is focused on the worst localized test result (test 3.2), the adjusted pH of 5.90 triggers an additional acidic Z_4 penalty of -1. Combined with the Z_2 penalty of -6, the local base B_D rating drops to -7. Considering the almost certain presence of massive chloride concentrations given the $0.43 \Omega \cdot m$ reading, an extra penalty for neutral salts (Z_7) must logically be assumed in a real-world scenario, which would confidently push the B_D rating well below -10. This numerical output clearly

dictates that the zinc coating at this specific location is entirely inadequate to resist the environment and is subject to rapid dissolution.

The assessment using EN 12501-2 Table 2 is straightforward and brutal. The mean pH is acceptable, but the mean resistivity of $5.95 \Omega \cdot m$ is an order of magnitude lower than the $30 \Omega \cdot m$ safety threshold. Consequently, the standard classifies the soil surrounding the Pavia installation as imposing an unquestionably high corrosion load, perfectly validating the severe physical degradation visually observed at the base of the columns during the field inspection.

Plant of province of Rovigo (RO)

The agricultural site in Rovigo is characterized by a heavy clay structure. The pH values were highly consistent, recording 7.87, 7.90, and 8.00, yielding a mean of 7.92. The electrical resistivity was also relatively stable, with readings of 28.13, 23.81, and $26.88 \Omega \cdot m$, resulting in a mean of $26.27 \Omega \cdot m$.

For the hot-dip galvanized dual-axis trackers, the DIN 50929-3 B_D rating is applied. The adjusted mean pH of 7.82 sits comfortably in the optimal stability zone for zinc, scoring 0 for Z₄. The mean resistivity of $26.27 \Omega \cdot m$ incurs a moderate Z₂ penalty of -2. Utilizing realistic neutral assumptions for the buffer capacity and biological activity, the baseline mean B_D rating stabilizes at a very solid -2. This indicates a good level of protection where the zinc coating is expected to perform excellently. Testing the model with the worst-case single result of $23.81 \Omega \cdot m$ from test 4.2 does not alter the mathematical outcome, as it remains within the same 20 to $50 \Omega \cdot m$ scoring bracket defined by the standard.

However, as an extra consideration, the heavy clay matrix is prone to trapping fertilizer salts from the active crop rotations. If a future fertigation cycle heavily loads the soil with sulfates, introducing a Z₇ penalty of -2, the B_D rating would gently decline to -4, which still represents a highly manageable, good level of protection.

According to the EN 12501-2 Table 2 classification, the Rovigo site falls into a critical theoretical area. The mean pH of 7.92 is entirely safe, but the mean resistivity of $26.27 \Omega \cdot m$ is situated just below $30 \Omega \cdot m$ limit, in an intermediate zone. Therefore, the standard mathematically classifies the entire agricultural field as possessing a high-medium corrosion load. This evaluation highlights a slight divergence between the two standards; while DIN recognizes the protective value of the neutral pH to balance the resistivity, EN 12501-2 takes a more punitive stance based on the sub- $30 \Omega \cdot m$ resistivity.

Plant of Piacenza (University) The data from the university research site in Piacenza reveals another dense clay environment. The pH measurements were highly uniform at 7.70, 7.70, and 7.65, giving a mean of 7.68. The electrical resistivity recorded values of 20.20, 17.09, and $18.57 \Omega \cdot m$, resulting in a mean of $18.62 \Omega \cdot m$.

Calculating the DIN 50929-3 B_D rating for the galvanized truss structure highlights a slightly more aggressive baseline environment than Rovigo. The adjusted mean pH of 7.58 provides a neutral Z₄ score of 0. However, the mean resistivity of 18.62 Ω·m crosses a critical threshold in the standard, falling into the 10 to 20 Ω·m bracket, which doubles the Z₂ penalization to a score of -4. Summing this with realistic neutral assumptions for the remaining chemical parameters yields a baseline mean B_D rating of -4. This specific numerical value indicates a good protective capability of the zinc coating.

As an extra operative consideration, this site is subjected to intensive experimental agricultural rotations (maize, tomatoes, hops). This continuous manipulation strongly implies that the neutral assumptions for fertilizers might be too optimistic. If agricultural chlorides or sulfides accumulate due to localized treatments, generating minor extra penalties, the B_D rating could easily slide towards the -6 or -8 range, entering the satisfactory but borderline zone.

Applying the EN 12501-2 Table 2 matrix yields a predictable result. While the mean pH is situated in the central safe zone, the mean resistivity of 18.62 Ω·m is far below the 30 Ω·m requirement. The standard unequivocally assigns a high corrosion load to the site. The presence of the concrete foundation blocks cast perfectly flush with the ground level further exacerbates this theoretical load by introducing severe physical crevices where this highly conductive electrolyte can stagnate, overriding any positive buffering effects the soil might naturally possess.

Plant of Ora (BZ)

The alpine orchard installation in Ora features a mixed sand-silt soil matrix. The pH values were recorded at 7.28, 7.67, and 7.60, producing a mean of 7.52. The electrical resistivity demonstrated significant spatial variation, with readings of 18.52, 48.66, and 15.87 Ω·m, giving a mean of 27.68 Ω·m.

For the hot-dip galvanized foundation piles supporting the Corten superstructure, the DIN 50929-3 B_D rating is necessary. Using the mean values, the adjusted pH of 7.42 scores 0 for Z₄, and the mean resistivity of 27.68 Ω·m incurs a Z₂ penalty of -2. Utilizing realistic neutral assumptions for unmeasured parameters, the baseline mean B_D rating is established at an excellent -2.

However, the spatial heterogeneity of the site drastically alters the risk profile. When applying the calculation to the worst-case localized test result (test 6.3), the resistivity drops to 15.87 Ω·m. This local drop forces the Z₂ resistivity score into the -4 penalty bracket, dragging the specific localized baseline B_D rating down to -4. Furthermore, as an extra consideration, the direct structural coupling of the galvanized pile to the noble Corten superstructure creates a massive external cathode. While the B_D rating defines the free soil corrosion, this bimetallic design essentially guarantees rapid anodic consumption of the zinc layer via macroscopic galvanic currents, rendering the

seemingly benign soil B_D rating practically irrelevant to the true lifespan of the foundation.

The evaluation through EN 12501-2 Table 2 reinforces the critical nature of the site. The mean pH is acceptable, and the mean resistivity of 27.68 $\Omega\cdot\text{m}$ is precariously close to the 30 $\Omega\cdot\text{m}$ boundary, technically placing it in the high corrosion load category. More importantly, the standard strictly dictates that wide variations in resistivity across the site force an immediate upgrade in the risk classification. The extreme fluctuation from 48.66 $\Omega\cdot\text{m}$ down to 15.87 $\Omega\cdot\text{m}$ between different test points guarantees the presence of powerful macroscopic concentration cells along the tracker rows, confirming beyond doubt that the structure operates under a high corrosion load.

5.3. Structural conditions and surface analysis

The evaluation of the physical degradation of the installed metallic infrastructures represents the concluding analytical phase of the experimental field campaign. To accurately assess the health of the structures, the measurement of the residual zinc coating was extensively tested in the field across multiple active solar plants. However, during the initial phases of the instrumental data collection, several critical challenges emerged. Following various measurement attempts where the collected data yielded completely nonsensical or erratic thickness values, a methodological investigation was necessary to determine the root cause of these instrumental anomalies. The principal problem deduced from this troubleshooting phase was the absolute lack of a pristine sample of the original base material to be utilized as a zero-reference baseline for the electromagnetic thickness gauges.

Specifically, the core issue is intrinsically linked to the metallurgical phenomenon known as the Sandelin effect. When steel profiles are subjected to the hot-dip galvanizing process, the specific concentration of silicon within the base steel dictates the reactivity of the alloy. In steels with certain silicon contents, the reaction between iron and liquid zinc becomes excessively rapid and linear, rather than parabolic. This distinct Sandelin effect leads to the uncontrolled formation of the final galvanization thickness, creating chaotic, mixed microstructural phases of iron and zinc alloys that extend all the way to the outer surface of the coating, rather than forming distinct, predictable layers of pure zinc over an alloy base [30] [71]. This distinct Sandelin effect leads to the uncontrolled formation of the final galvanization thickness, creating chaotic, mixed microstructural phases of iron and zinc alloys that extend all the way to the outer surface of the coating, rather than forming distinct, predictable layers of pure zinc over an alloy base [30] [71]. When an electromagnetic probe attempts to measure the coating, these mixed magnetic phases completely falsify the reading, as the instrument cannot discern a clear boundary between the steel substrate and the protective layer. Consequently, it is absolutely necessary to have prior technical data

regarding the exact chemical composition of the base steel and to make direct reference to a clean sample of the specific material batch to properly calibrate the instruments. Due to these metallurgical complexities, there remains a strong necessity for further dedicated tests to definitively validate the effectiveness and accuracy of this specific field detection methodology.

Plant 1: province of Modena (MO)

The structural evaluation of this specific plant focuses on the behavior of the unalloyed weathering steel utilized for the foundation profiles. Because the installation is of entirely new construction, it currently presents the very early developmental stages of the protective Corten patina, possessing a historical tracking period of only 1 year. It was observed that the steel profiles were driven into the ground for supply reasons without the protective patina having already developed beforehand. Currently, the development of the aerial patina exhibits a reddish-orange coloration that is still relatively light, a chromatic state that is entirely coherent with the brief period of atmospheric exposure that has elapsed since construction.



Figure 22 - Buried part of plant of Modena

Transitioning to the underground structural condition, the steel presents a highly distinct degradation pattern. In the telluric environment, there is a patchy corrosion distribution that is fully consistent with the anticipated pitting development model expected in the area situated below the first 10 cm of the excavated soil. Analyzing the material loss specifically, the aerial portion of the plant has responded with the initial, uniform development of a protective patina. Conversely, there is a complete absence

of any protective patina in the first 10 cm of the subsoil. Moving deeper into the underground section, specifically towards the 20 to 30 cm depth range, the development becomes much brighter and exhibits deep, uneven, and patchy marks. This specific underground behavior indicates an environment that is highly prone to localized patchy pitting, completely diverging from the uniform passivation observed in the aerial section above ground.

Plant 2: province of Vercelli (VC)

The structural conditions of the second investigated site are entirely dictated by its current developmental phase. Because the massive solar plant is actively under construction, the metallic foundation profiles do not present any visible signs of corrosion or structural degradation at this time. The hot-dip galvanized coating remains visually intact and pristine across the observed structural members.



Figure 23 - Foundation part of plant of Vercelli

However, the surface analysis and site observation allowed for the identification of severe structural risk areas that will inevitably influence the future corrosion rate of the plant. The most critical vulnerability is located precisely at the base of the concrete plinths. This specific risk is generated by the geometric configuration of the foundation, particularly its depth relative to the surrounding soil, which leaves the interface situated 10 cm below the natural ground level. This sunken configuration leads to a severe stagnation of water during the winter period, completely submerging the critical junction between the galvanized steel and the concrete matrix. Because the plant is still in the active construction phase and lacks any historical exposure data, an analysis of the actual zinc loss compared to the estimated thickness is currently not evaluable.

Plant 3: Pavia (PV)

The structural condition of the university parking canopy reveals a severe state of advanced degradation. A highly aggressive corrosive ring is clearly visible approximately 7 cm above the contact line between the vertical pole and the concrete plinth. This specific localized area is affected by profound corrosion phenomena that have progressed to the point of causing active flaking of the underlying structural steel. Furthermore, there is a distinct chromatic shift in the metallic surface in the area immediately above this ring, accompanied by aggressive pitting phenomena exactly at the air-soil transition zone. The deeply buried underground portion of the poles is completely and entirely corroded. Interestingly, the foundation columns that utilize only concrete plinths without topsoil do not present these signs of corrosion, which strongly suggests that the severe degradation problem derives directly from the filling of the foundation areas with mixed soil and gravel. Additionally, in the aerial portion of the structure, specific corrosion spots are visible on the fixing beads of the solar panels, exactly corresponding to the water drainage points.



Figure 24 - Foundation and buried part of plant of Pavia

Analyzing the material loss based on the 13 years that have passed since the plant's construction, it is evident that the protective zinc layer has been entirely consumed in the critical zones. Because there is active flaking of the base steel, it is a certainty that the zinc layer was completely exhausted several years ago. Estimating that the coating failed at least 3.5 years ago, the calculation assumes a functional lifespan of roughly 9.5 years for the original layer. Given an assumed initial galvanization thickness of 90 μm , this severe degradation translates to an estimated annual zinc loss rate equal to or greater than 9.47 $\mu\text{m}/\text{year}$.

Plant 4: province of Rovigo (RO)

The inspection of the foundations at this massive agricultural site revealed a surprisingly pristine structural condition. Despite the installation being decidedly old, having been originally constructed in 2013, the foundation poles do not present any visible trace of corrosion. This excellent state of preservation is consistent across the entire length of the structure, showing no signs of degradation either in the buried underground portion or in the aerial section exposed to the agricultural atmosphere.



Figure 25 - Buried part of plant of Rovigo

Regarding the analysis of the material loss, the lack of any significant deterioration makes precise calculations challenging. Since there are no numerical values of degradation to record and an absolute absence of any chromatic shading or rust at the structural boundaries, the surface remains highly stable. Consequently, the massive steel poles present an estimated corrosion rate in the order of mere tenths of a μm per year. Based on this exceptional structural stability over the extended lifespan of the plant, the overall material loss is confidently estimated to be extremely low, hovering around $0.5\text{-}2\ \mu\text{m}/\text{year}$.

Plant 5: Castelvetro (PC)

The structural assessment of this elevated installation highlights a stark contrast between the aerial and foundational elements. Despite the considerable age of the plant, the aerial portion of the structure presents absolutely no signs of corrosion. This excellent preservation is largely due to the combined protective solution of utilizing an industrial paint over the hot-dip galvanization, coupled with the elevated concrete foundations that isolate the main poles from the immediate soil surface. However, severe corrosion is undeniably present at the specific attachment point between the

metal pole and the foundation matrix. At this interface, there is a connection steel joint that is now entirely corroded. Because there are no traces of thick corrosion flakes, but rather a surface porosity in the material, it is hypothesized that the zinc coating in this specific ring has only recently been completely exhausted.



Figure 26 - Foundation of plant of Castelvetro

The analysis of the zinc loss perfectly reflects these visual observations. The main pole does not present any exposed degraded zinc, and the paint in the aerial section is still intact. Therefore, the estimated decay of the galvanization in the aerial zone is precisely $0 \mu\text{m}/\text{year}$. In stark contrast, evaluating the heavily corroded contact ring requires a different estimation. According to the ISO 1461 standard, a steel profile with a thickness exceeding 6 mm would have originally possessed an average zinc thickness of at least $85 \mu\text{m}$. Assuming a slightly conservative initial value of $100 \mu\text{m}$ for this specific heavy-duty component, and factoring in the operational age of the plant, the calculation presupposes a significant localized annual loss rate of $7.7 \mu\text{m}/\text{year}$ at the foundation node.

Plant 6: Piacenza (PC)

The physical condition of the university research truss structure is defined by its extremely recent installation. Consequently, there are absolutely no signs of active environmental corrosion present on the metallic surfaces. The only visual anomalies observed on the pristine framework are specific dark and shiny galvanization marks.

These localized surface variations are hypothesized not attributed to environmental degradation, but are instead thought to be the physical result of the mechanical screwing process during the foundation installation, or potentially the very first microscopic signs of localized environmental attack.



Figure 27 - Buried part of plant of Piacenza

Due to the extreme youth of the plant, the historical data available is entirely insufficient to execute a reliable empirical estimate of the zinc loss over time. However, based on theoretical models for this environment, the degradation is expected to remain within contained values, remaining minor or equal to the theoretical estimates of 4 to 5 $\mu\text{m}/\text{year}$. Despite this optimistic baseline, particular and continuous attention must be paid to the shiny spots identified during the inspection, as they represent the most likely points of failure for any eventual future degradation analysis.

Plant 7: Ora (BZ)

The structural evaluation of the alpine orchard installation reveals a condition largely influenced by its recent commissioning and specific material choices. Because the plant is entirely new, there is absolutely no corrosion present on the hot-dip galvanized profiles within the underground soil environment. However, a highly specific and active corrosion phenomenon was detected in the aerial portion of the structure. Specifically, early signs of corrosion are visibly developing exactly at the physical point of contact between the unalloyed Corten weathering steel superstructure and the hot-dip galvanized foundation piles. This bimetallic interface is located on the main pole, situated relatively close to the ground level.



Figure 28 - Buried part and connection joint of plant of Ora

Similar to the previous recently constructed site, the operational history of this installation is insufficient to perform a concrete mathematical estimation of the annual zinc loss. The material depletion is expected to stay within contained boundaries, remaining minor or equal to the standard theoretical estimates of 4 to 5 $\mu\text{m}/\text{year}$ for the general surface area. The localized galvanic cell created by the bimetallic coupling, however, dictates the primary structural risk for this specific plant giving an estimate degradation of 15 to 30 $\mu\text{m}/\text{year}$ in the contact area.

Plant 8: Almeria (Spain)

The inspection of the experimental coastal installation revealed a surprisingly severe and aggressive state of degradation, especially considering the extreme youth of the structure. Active corrosion is clearly visible across the aerial portions of the metallic framework. Following a deeper investigation into the agronomic practices of the site, this rapid deterioration was directly attributed to the heavy agricultural use of elemental sulfur and its various chemical derivatives, specifically sulfates and sulfides, which are routinely applied to the vineyard as targeted fertilizers and organic treatments.



Figure 29 – Metallic frameworks of plant of Almeria

The analysis of the zinc loss highlights a catastrophic failure of the protective coating. Despite the very young age of the installation, the supporting poles already present distinct rust spots where the protective zinc layer has been completely exhausted. The lack of heavy steel flakes suggests that the zinc layer has only very recently finished its protective life cycle. Reaching the complete exhaustion of the standard hot-dip galvanization layer in a mere 12 months of exposure yields a remarkably high and damaging corrosion rate, precisely equating to a massive loss of $45 \mu\text{m}/\text{year}$.

Plant 9: Barcelona (Spain)

The final investigated installation, situated in the coastal metropolitan area, currently exhibits a pristine structural condition. Due to the very recent installation of the tracking framework, there is absolutely no active corrosion present on the massive hot-dip galvanized profiles. The structural surfaces remain uniform and visually uncompromised by the surrounding agricultural environment.



Figure 30 - Piles of plant of Barcelona

While the current physical state is perfect, the surface analysis must account for the specific environmental context. The structure faces significant further degradation risks derived directly from its immediate proximity to the sea, a geographical factor that strictly classifies the operational environment within the highly aggressive C4 atmospheric corrosivity category. Because the plant is newly commissioned, the historical timeline is currently insufficient to perform an empirical estimation of the material loss. Nevertheless, barring the onset of severe localized maritime effects, the general material degradation is theoretically expected to remain within contained values, estimated to be minor or equal to the theoretical baseline of 4 to 5 $\mu\text{m}/\text{year}$, with a possible increase to a 5.5 - 6.5 $\mu\text{m}/\text{year}$ due to high presence of chlorides.

6 Chapter 6: critical analysis and discussion

6.1. Correlation between soil parameters and corrosion

The fundamental objective of an environmental survey in the context of solar infrastructure is to establish a reliable predictive link between the physico-chemical properties of the telluric electrolyte and the actual physical degradation of the buried metallic supports. The experimental data collected during the field campaigns provide a vital opportunity to validate the theoretical models established by international normative standards. By correlating the specific hydrogen ion concentration (pH) and the electrical resistivity measured in the previous chapters with the physical surface analysis, it becomes possible to understand the true aggressive dynamics of the agrivoltaic environment. This analysis clearly demonstrates that while general soil corrosivity matrices, such as the European standard EN 12501-2, offer a broad conservative baseline, the multifactorial logic of the German standard DIN 50929-3 provides a much more accurate reflection of the complex phenomena occurring in the field. Furthermore, the historical data gathered by Melvin Romanoff regarding the underground corrosion of galvanized steel serves as a crucial comparative baseline to evaluate the specific accelerating factors introduced by modern agricultural practices.

Plant of Province of Modena (MO)

The recently constructed agrivoltaic system in Modena provides vital data regarding the behavior of unalloyed weathering steel in specific telluric environments. The physical inspection revealed that while the aerial portion of the structure was developing a uniform, protective oxyhydroxide patina, the underground portion located in the first 30 cm of the subsoil was exhibiting deep, uneven, and patchy marks, indicating the rapid onset of localized pitting.

This physical phenomenon correlates seamlessly with the measured soil parameters and the resulting normative ratings. The soil is characterized by a heavy clay matrix with poor aeration and high water retention, maintaining a constantly saturated state due to the high water table. While the mean pH of 7.70 is safely alkaline, the electrical resistivity is relatively low at 17.43 $\Omega \cdot m$. The DIN 50929-3 standard calculated a comprehensive index predicting a medium to high corrosion load. The physical lack of a protective patina underground confirms the metallurgical theory that Corten

requires alternating wet and dry cycles and abundant oxygen to passivate. Buried in a highly conductive, wet, and anoxic clay, the weathering steel behaves precisely like standard carbon steel, concentrating the anodic dissolution in small, localized pits driven by the differential aeration cell established at the muddy ground level. Therefore, despite its young age, the correlation indicates that this structure will undoubtedly face severe localized corrosion problems during its intended service life.

Plant of province of Vercelli (VC)

The massive single-axis tracking plant in Vercelli is currently in its initial operational phase, showing no present signs of corrosion on its heavily galvanized profiles. The baseline soil parameters present a sandy matrix with a neutral pH of 7.32 and a moderate resistivity of $26.31 \Omega \cdot m$, which generated a good protective rating according to the DIN standard. Based purely on the homogeneous soil chemistry, the structures should comfortably survive their operational lifespan.

However, a critical review of the structural design in relation to the specific hydrogeological environment completely alters the future durability prognosis. The concrete foundation plinths were purposefully sunken 10 cm below the natural ground level. Because the site is located in an area historically dedicated to flooded rice paddies, the water table frequently rises to the surface, causing severe water stagnation exactly at this geometric depression. According to the DIN standard, this specific scenario must be evaluated using the parameters for the water and air interface, which immediately introduces a massive penalty due to the localized concentration of the corrosive attack. While the deep soil parameters are benign, this constant stagnation of potentially fertilizer-laden water at the steel-concrete interface will inevitably create a powerful differential aeration cell. Consequently, it is highly predictable that this plant will suffer from premature, localized steel depletion and subsequent necking at the waterline long before the deep underground sections show any significant wear.

Plant of Pavia (PV)

The installation located at the university campus in Pavia represents the most definitive and severe confirmation of the electrochemical principles governing underground corrosion. The correlation between the measured soil parameters and the observed structural degradation is textbook in its accuracy. The geochemical survey revealed a slightly acidic to neutral mean pH of 6.82, but the critical defining factor was the catastrophic drop in specific electrical resistivity. With a mean value of $5.95 \Omega \cdot m$ and localized drops reaching an astonishing $0.43 \Omega \cdot m$, the telluric environment was transformed into a highly conductive electrolyte.

The DIN 50929-3 mathematical model accurately translated these parameters into a highly inadequate protective rating. The physical inspection of the 13 year old structures perfectly mirrored this dire prediction. The low pH combined with the

extremely low electrical resistivity led to a very marked corrosion effect exactly at the air-soil transition zone. The protective zinc layer was completely exhausted several years prior to the inspection, leading to active flaking of the underlying structural carbon steel. The calculated material loss rate exceeding $9.47 \mu\text{m}/\text{year}$ validates the theoretical premise that highly conductive soils bypass any natural passivating mechanisms, providing a path of least resistance for powerful macroscopic galvanic currents to dissolve the anodic zinc coating.

Plant of province of Rovigo (RO)

The agricultural site in Rovigo provides the perfect counter-narrative to the Pavia installation, demonstrating how a favorable combination of soil parameters can preserve buried steel indefinitely. Despite sharing the exact same operational age of 13 years, the structures at Rovigo showed no visible signs of corrosion, maintaining a pristine galvanized surface with a negligible material loss estimated at around $0.5 - 2 \mu\text{m}/\text{year}$.

This excellent state of preservation is directly correlated to the specific soil chemistry measured during the campaign. The heavy clay structure presented a highly alkaline mean pH of 7.92 and a relatively high electrical resistivity of $26.27 \Omega\cdot\text{m}$. The DIN 50929-3 standard accurately processed these values, yielding a highly positive score indicative of a good protective environment. The high pH acts as a powerful chemical buffer, stabilizing the zinc carbonate passivation layer on the surface of the foundations and preventing its dissolution. It is highly notable that the EN 12501-2 standard classified this site as having a high corrosion load simply because the resistivity was below the strict $30 \Omega\cdot\text{m}$ threshold. The physical reality of the pristine poles proves that the EN standard is excessively punitive and that the DIN standard's method of balancing moderate resistivity with alkaline pH buffering provides a much more accurate correlation to the actual lifespan of the structure.

Plant of Castelvetro (PC)

The advanced agrivoltaic installation in Piacenza offers a unique perspective on the intersection of long-term agricultural exposure and protective engineering. Being one of the oldest active systems investigated, dating back to 2011, it has a significant operational history within an intensive farming context. While exact numerical values of the soil pH and conductivity were not available for this site, the physical evidence allows for a strong inferential correlation regarding the aggressiveness of the environment.

The structural design utilized massive concrete foundations elevated above the ground level, coupled with a double protective barrier consisting of hot-dip galvanization completely sealed by industrial paint. This heavy-duty engineering acted as an impenetrable barrier against the telluric electrolyte, resulting in the complete preservation of the main aerial structure. However, severe degradation was

localized exclusively at the single unprotected node: the steel attachment plate at the interface between the steel pole and the concrete matrix. The active agricultural context, characterized by the continuous application of fertilizers and irrigation, invariably lowers the soil resistivity and alters the local pH. Positioned exactly at the critical air-soil transition zone, this unprotected ring suffered a severe localized attack, yielding a calculated corrosion rate of $7.7 \mu\text{m}/\text{year}$. This rate represents a significant worsening compared to the historical average of $5.34 \mu\text{m}/\text{year}$ established by the extensive underground corrosion investigations conducted by Romanoff [19] for galvanized steel in standard, undisturbed soils. This demonstrates that even when the main structure is protected, the specific combination of agricultural chemistry and differential aeration at the ground interface drastically accelerates the local corrosion kinetics.

Plant of Piacenza (PC)

Similar to Vercelli, the university research truss structure in Piacenza is extremely new and currently exhibits only minor mechanical installation marks rather than environmental corrosion. The heavy clay soil presented a highly uniform alkaline pH of 7.68 and a resistivity of 18.62 m , crossing a normative threshold that doubled the penalization in the DIN matrix, resulting in a baseline rating that still theoretically indicates a good to satisfactory protective capability for the zinc coating.

However, the correlation between the environment and future durability must account for the primary purpose of the site. As a dedicated university testbed, the soil is subjected to highly intensive and varied agricultural crop rotations. This continuous manipulation guarantees that the neutral baseline assumptions regarding chemical contaminants will soon be violated. The periodic introduction of nitrates and sulfates will act to further depress the electrical resistivity and consume the alkaline buffer. Furthermore, the foundations consist of concrete bases cast perfectly flush with the ground level, creating physical crevices where conductive agricultural runoff can easily stagnate. While the robust $90 \mu\text{m}$ zinc layer provides an excellent initial barrier, the combination of a naturally conductive clay matrix with the anticipated accumulation of agronomic chemicals suggests that the corrosion rate will slowly accelerate, eventually posing localized maintenance challenges during the later stages of its useful life.

Plant of Ora (BZ)

The alpine orchard installation in Bolzano provides perhaps the most striking example of how structural design choices can completely invalidate the protective capacity of the surrounding soil. The geotechnical survey of the mixed sand-silt matrix revealed a safe pH of 7.52 and a resistivity of $27.68 \Omega\cdot\text{m}$. The application of the DIN 50929-3 standard produced an excellent rating, indicating that the hot-dip galvanized

foundation piles should experience very slow, manageable corrosion rates in a free-soil environment.

However, the physical inspection of this brand-new plant already revealed early, active signs of corrosion developing exactly at the aerial point of contact near the ground level. This rapid onset of degradation is the direct result of a deliberate bimetallic combination: the hot-dip galvanized foundation piles are physically bolted to an entire superstructure manufactured from unalloyed Corten steel. This architectural choice creates a massive, permanent galvanic cell. In the presence of moisture, the noble Corten acts as a vast external cathode, forcing the zinc coating on the foundation pile to act as a sacrificial anode for the entire tracker framework. The benign telluric parameters (pH and conductivity) that generated the positive DIN rating are rendered entirely secondary. The powerful macroscopic galvanic currents will guarantee the rapid, accelerated dissolution of the protective zinc layer, making severe structural corrosion a certainty well within the expected service life of the plant, despite the inherently safe nature of the alpine soil.

Plant of Almeria

If the historical plants demonstrate the slow, predictable effects of basic soil parameters, the experimental installation in southern Spain highlights how extreme agronomic management can instantaneously override any standard theoretical baseline. The plant is of extremely recent construction, having been installed only one year prior to the inspection. Under normal circumstances, regardless of the precise base pH or electrical conductivity of the dry sandy soil, a standard hot-dip galvanized coating should show negligible wear after only twelve months of exposure.

However, the physical inspection revealed a catastrophic failure of the protective coating, with a massive localized zinc loss calculated at 45 $\mu\text{m}/\text{year}$, accompanied by the premature appearance of red rust. The primary driver for this severe degradation was completely divorced from the natural telluric baseline; rather, it was the direct result of the massive and frequent application of elemental sulfur and sulfate-based agricultural fertilizers. These chemicals, utilized for organic viticulture, reacted violently with the moisture to create a highly acidic and conductive micro-environment directly on the metallic surfaces. This extreme situation proves that when a structure is poorly designed for its specific operational use, the direct chemical attack kinetics of aggressive fertilizers will trigger immediate and severe deterioration, rendering the standard measurements of background pH and conductivity practically irrelevant to the actual survival of the infrastructure.

Plant of Barcelona

The dynamic tracking installation in Spain presents a unique challenge in predictive correlation because it combines two distinct corrosive environments. Because the framework was installed very recently, the massive 90 μm hot-dip galvanized coating

remains visually perfect and structurally uncompromised. Without long-term extraction data, the precise material loss cannot yet be mathematically defined.

However, an evaluation of its future durability must be framed by its specific geographical location. Situated in a coastal metropolitan area, the ambient atmosphere is strictly classified within the highly aggressive C4 corrosivity category due to the constant presence of marine aerosols and high baseline humidity. This severe atmospheric load is then compounded by the agrivoltaic layout itself. The intensive cultivation of vegetables directly beneath the solar panels generates continuous evapotranspiration, further elevating the local microclimate humidity and prolonging the time of wetness on the metallic surfaces. While the underground soil parameters remain unknown, the synergistic effect of maritime chlorides and agricultural moisture practically guarantees that the aerial degradation of the zinc coating will significantly exceed the standard theoretical baseline of 4 to 5 $\mu\text{m}/\text{year}$ typically expected in rural environments, reaching an estimated degradation of 5.5 to 6.5 $\mu\text{m}/\text{year}$. The heavy-duty specification of the 90 μm coating was a necessary engineering choice to combat this combined attack, but rigorous monitoring will be required to ensure it survives the full design life.

6.2. Comparative analysis with vineyard posts

The evaluation of underground corrosion in agrivoltaic systems presents a unique scientific challenge, as the sector currently lacks long-term historical data strictly related to dual-use solar foundations. To bridge this temporal gap and empirically validate the theoretical models of agricultural corrosion discussed in previous chapters, it is highly effective to conduct a comparative analysis with infrastructures that have shared the exact same operational environment for decades. Vineyard posts represent the most accurate proxy available for agrivoltaic foundation piles. Both structures are driven directly into cultivated soils, share similar open geometric profiles, utilize identical protective metallic coatings, and, most importantly, are subjected to the exact same continuous chemical stress derived from agricultural practices, such as irrigation cycles, pesticide application, and intensive fertilization.

To provide a direct and practical assessment of these aggressive dynamics, this section analyzes a specific technical case study provided by an industrial manufacturer of agricultural steel poles, Valente SRL. The failure investigation was conducted by the ArcelorMittal Global Research and Development center located in Ghent. The object of the study is a set of severely corroded vineyard poles extracted from the soil after a remarkably short operational period of only three years. The comprehensive failure analysis of these profiles, which includes meticulous geotechnical profiling and advanced microscopic metallography, perfectly illustrates the accelerated degradation

kinetics that threaten agrivoltaic foundations if the agricultural variables are not properly integrated into the structural design phase.



Figure 31 - Integration of structural support and grapevine [34]

The investigated vineyard poles were manufactured using a structural carbon steel substrate, specifically grade S250. To protect this steel core against the environmental elements, the profiles were coated with an advanced continuous zinc-aluminum-magnesium alloy, commercially known as Magnelis. The specific coating designation applied to these poles was ZM310. According to the technical specifications of the material, a ZM310 designation indicates a total minimum coating mass of 310 g/m² distributed across both surfaces. When converted to a linear physical dimension, this mass corresponds to a theoretical guidance value of approximately 25 µm of protective alloy per side [34].

Under standard, ordinary atmospheric conditions, such as those classified as C3 medium corrosivity, manufacturer data and accelerated salt spray tests consistently demonstrate that a 25 µm zinc-aluminum-magnesium layer can easily guarantee a service life exceeding forty to fifty years without the appearance of red rust. The advanced microstructure of the alloy, characterized by a complex ternary eutectic phase containing magnesium, provides exceptional barrier properties and a highly effective self-healing effect on cut edges in open-air environments [34].



Figure 32 - Visual assessment of corrosion and rust distribution on a vineyard post specimen [34]

However, the specific condition that led to the severe corrosion of these poles was not atmospheric exposure, but rather their direct burial in an active, heavily manipulated agricultural soil. After only three years of service, the end-user extracted the poles from the vineyard and observed massive structural degradation. The initial visual inspection of the delivered samples at the laboratory revealed a stark contrast. The portion of the pole exposed to the air maintained its structural integrity and the characteristic appearance of the protective alloy. Conversely, the buried section, particularly the critical transition zone extending from the soil line downwards, was heavily covered in voluminous, reddish-brown corrosion products. This macroscopic evidence indicated that the 25 μm protective alloy had been completely consumed, and the underlying carbon steel substrate was actively and rapidly dissolving.

To attempt to mitigate this well-known vulnerability precisely at the air-soil interface, the manufacturer had actually implemented a supplementary passive protection strategy. After the mechanical profiling process, the poles were plunged into a paint bath, receiving an application of a red coating followed by a transparent layer specifically localized at the ground level transition zone. Despite this manufacturing precaution, the unpainted deeply buried sections, as well as the areas where the paint might have been mechanically damaged during the heavy friction of the driving process, suffered a rapid and severe electrochemical attack.

Comparing this rapid failure to ordinary environmental conditions highlights the extreme discrepancy between natural soil aggressiveness and agriculturally modified soil aggressiveness. In a standard, uncultivated terrain characterized by high electrical resistivity and a neutral hydrogen ion concentration, a 25 μm advanced zinc-magnesium coating would be expected to deplete very slowly, providing at least a decade or two of continuous sacrificial protection before the onset of base metal corrosion. The catastrophic failure within a mere thirty-six months indicates the presence of a highly aggressive, low-resistivity electrolyte continuously renewing its chemical attack on the amphoteric zinc and magnesium phases of the coating.

To scientifically quantify the absolute corrosivity of this specific vineyard environment, the soil extracted directly alongside the corroded poles was subjected to

a rigorous physico-chemical analysis in accordance with the German standard DIN 50929-3. This specific standard, as detailed in the methodology chapters, evaluates the probability of free corrosion by assigning weighted algebraic scores, known as Z parameters, to various intrinsic soil properties in order to calculate an overall corrosion load index known as B_0 . The laboratory results revealed a highly critical geotechnical profile that perfectly explains the rapid metallic degradation.

The mechanical texture of the soil was determined to be predominantly clayey, with a massive clay fraction of 65.1 % by mass, accompanied by 32.6 % silt and a negligible 2.3 % sand. In the DIN 50929-3 evaluation framework, heavy clay soils severely restrict oxygen diffusion and retain moisture tightly, fostering the creation of powerful differential aeration cells and anoxic conditions at depth. Consequently, the soil texture was assigned a strongly negative Z_1 parameter score of -4. Furthermore, the gravimetric soil moisture was measured at a high 34.92 % by mass, reflecting the high water retention capacity of the dense clay and the highly probable presence of agricultural irrigation cycles. Because this specific value far exceeds the 20 % threshold defined by the standard for optimal aeration, the moisture content received a Z_3 score of -1.

However, the absolute most decisive parameter in the entire geotechnical evaluation was the specific electrical resistivity. The direct measurement of the soil sample exactly as received yielded a value of 101 $\Omega\cdot\text{m}$. Yet, for a correct electrochemical interpretation according to the dictates of the standard, the absolute minimum soil resistivity in a completely saturated state must be utilized. The laboratory determined this minimum soil resistivity to be an exceptionally low 8.33 $\Omega\cdot\text{m}$. This extremely low resistance to electrical current flow provides a perfect, unimpeded medium for galvanic macrocells to operate. According to the DIN evaluation tables, a resistivity dropping below 10 $\Omega\cdot\text{m}$ incurs the maximum possible penalization for this category, resulting in a devastating Z_2 parameter score of -6.

Other chemical parameters offered a slightly more benign profile but could not mathematically or physically offset the critical resistivity and the stifling clay texture. The soil pH was mildly alkaline at a value of 8.2, which falls within the optimal thermodynamic stability window for zinc carbonates, resulting in a neutral Z_4 score of 0. The alkalinity titration up to pH 4.3 revealed a high buffer capacity of 1794 mmoles per kilogram, indicating that the soil successfully resists sudden drops in pH, earning a positive Z_5 score of +1. Neutral salts and sulfides, common natural drivers of corrosion, were actually below critical detection limits, yielding neutral scores for the Z_6 , Z_7 , Z_8 , and Z_9 parameters.

Algebraically summing these individual Z parameters yields a final B_0 index of -10. According to the standard's comprehensive classification matrix, a B_0 score of -10 unequivocally categorizes the soil as having a high corrosion load. The predictive engineering models associated with this specific high load are alarming for thin-

walled structural profiles. The expected uniform corrosion rate for bare carbon steel in this specific environment is estimated at 60 μm per year. Even more critically, the likelihood of localized attack is extremely high, with an estimated pitting corrosion rate that can reach up to 400 μm per year [46]. This theoretical calculation perfectly aligns with the rapid structural failure actually observed in the field, confirming beyond doubt that the soil was inherently destructive to the metallic foundation.

While the DIN 50929-3 standard successfully identifies the dangerously low resistivity through its mathematical scoring, it does not inherently explain its specific origin, especially since the standard naturally occurring chlorides and sulfates were found to be below detection limits. To uncover the root cause of this massive electrical conductivity, the researchers performed an additional chemical analysis focused explicitly on agricultural inputs. The results confirmed the massive presence of artificial fertilizer residues. The soil extract revealed a nitrate concentration of 36000 and a substantial phosphate content, expressed as phosphorus pentoxide, of 0.2 % by mass. Furthermore, a significant concentration of copper at 78 ppm was detected. While the technical report notes this copper level is relatively average for generic topsoils, in the specific context of a vineyard or intensive agriculture, it is an unmistakable chemical signature of the long-term, repeated application of copper-based fungicides, such as the classic Bordeaux mixture.

These specific agricultural products act as the primary catalysts for the structural degradation. Nitrates and phosphates are highly soluble salts. When introduced into the dense clay matrix, they dissolve completely into the pore water, providing an abundance of free ions that drastically plummet the electrical resistivity from a naturally benign state down to the critical 8.33 $\Omega\cdot\text{m}$ measured in the laboratory. Nitrates also act as strong chemical oxidizing agents, capable of depolarizing the cathodic reaction and severely accelerating the anodic dissolution of the zinc-aluminum-magnesium layer. The complex interaction of this artificial agricultural electrolyte with the structural metal was further elucidated through advanced microscopic techniques.

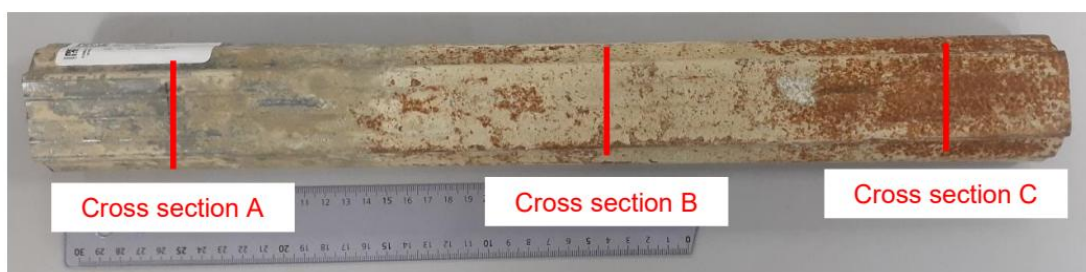


Figure 33 - Identification of cross-sections for localized corrosion analysis on a support post specimen [34]

To rigorously evaluate the exact morphological state of the residual coating and identify the active corrosion mechanisms at a microscopic level, cross-sectional

analyses were meticulously performed on the most degraded portion of the extracted pole using a Scanning Electron Microscope equipped with a Backscattered Electron detector. Backscattered Electron imaging is a particularly powerful tool in advanced metallography because the visual contrast in the resulting image is directly proportional to the atomic number of the elements present. Heavier elements, like the solid iron in the steel substrate, scatter more electrons and appear very bright, while lighter elements, like the oxygen and carbon trapped within the rust matrix, scatter fewer electrons and appear much darker. This technique allows for a highly distinct and unequivocal visual separation between the remaining healthy metal and the porous corrosion crust.

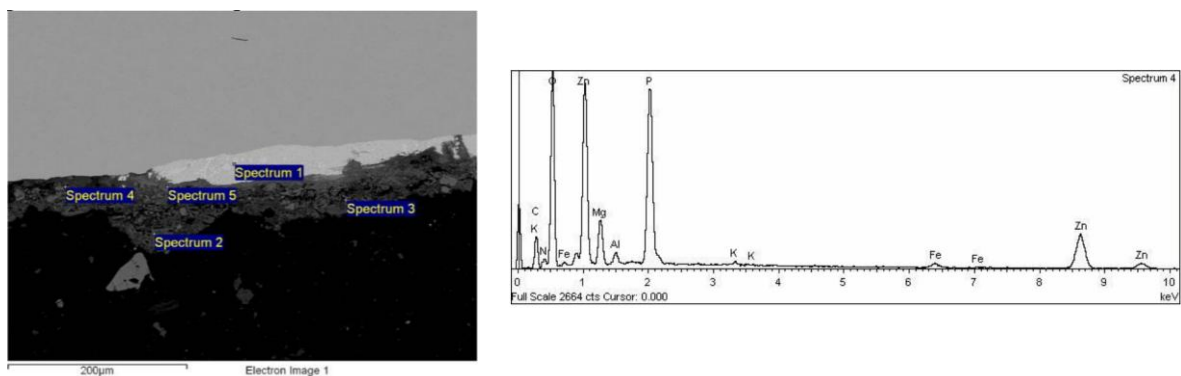


Figure 34 - BSE image of cross section A showing the acquisition points for EDX analysis (left) and the corresponding EDX spectrum 4 (right) [34]

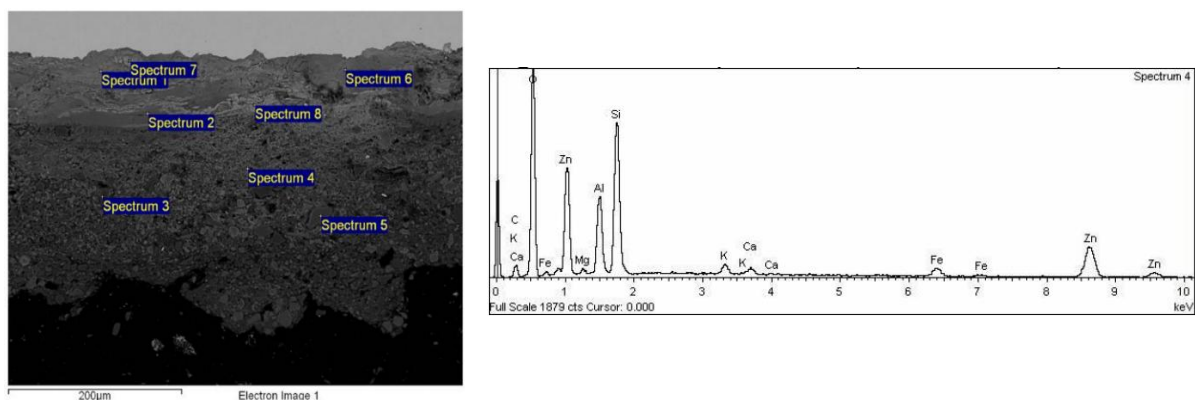


Figure 35 - BSE image of cross section B showing the acquisition points for EDX analysis (left) and the corresponding EDX spectrum 4 (right) [34]

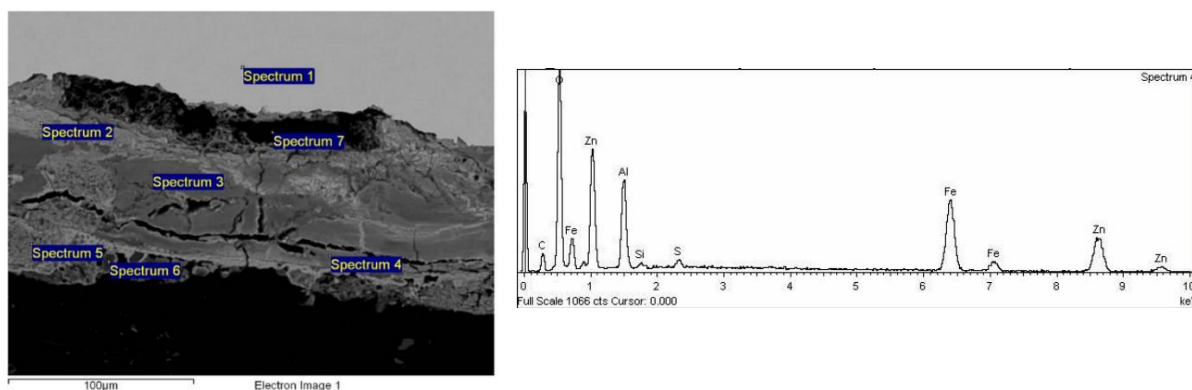


Figure 36 - BSE image of cross section C showing the acquisition points for EDX analysis (left) and the corresponding EDX spectrum 4 (right) [34]

The Backscattered Electron images of the pole cross-sections provided undeniable, highly magnified evidence of the catastrophic coating failure. Across multiple analyzed areas along the profile, the original 25 µm layer of the high-performance Magnelis alloy was completely obliterated; it was no longer visible as a distinct, bright metallic band protecting the core. Instead, it had been entirely transformed into a thick, highly porous, and structurally useless layer of complex corrosion products. The images clearly showed that the protective barrier was entirely breached, and the aggressive telluric electrolyte had reached the S250 carbon steel substrate. The physical boundary between the steel and the overlying corrosion layer was highly irregular and jagged, providing stark visual confirmation that the substrate was being actively attacked and continuously consumed.

Table 8 - EDX results cross section A (weight %) [34]

Spectrum	C	N	O	Mg	Al	P	S	K	Ca	Fe	Zn
1	7.3		1.0	2.6	3.5					0.8	84.9
2	15.5	4.5	37.2	0.6	0.6	13.2		0.4	0.3	0.4	27.4
3	38.7	4.0	22.8		0.2	10.1	0.2			1.8	22.1
4	20.9	4.4	37.2	3.3	0.6	10.9		0.2		0.7	21.7
5	11.9	3.5	34.8	0.3	3.7	8.7	0.6			0.6	35.9

Table 9 - EDX results cross section B (weight %) [34]

Spectrum	C	O	Na	Mg	Al	Si	S	K	Ca	Fe	Zn
1	6.8	34.7			2.5				0.3	40.8	15.0
2	9.5	39.7			15.1		0.6		0.3	5.1	29.7
3	14.4	55.1		11.0		0.6			19.0		
4	11.8	45.0		0.5	6.3	12.3		1.0	0.7	2.5	20.1
5	5.4	48.3	0.4		8.2	26.6		10.9		0.2	0.03
6	8.6	35.0			6.6		0.4		1.1	1.4	46.9
7	5.9	38.6			0.3				0.3	52.2	2.8
8	8.8	34.8			7.8		0.3		0.3	22.2	25.7

Table 10 - EDX results cross section C (weight %) [34]

Spectrum	C	O	Mg	Al	Si	S	K	Fe	Zn
1	8.7							91.4	
2	10.3	31.4		1.0		0.3		35.3	21.8
3	9.6	38.2		10.1		1.1		8.8	32.3
4	10.6	35.4		7.8	0.4	0.7		19.7	25.5
5	11.7	42.0	0.3	1.6	2.9	0.3	0.5	28.6	12.4
6	6.7	54.2			37.7			1.4	
7	80.5	19.1						0.4	

To determine the exact chemical composition of these massive corrosion products, Energy Dispersive X-ray spectrometry was seamlessly utilized in tandem with the electron microscope. By precisely directing the electron beam at specific microscopic points within the dark corrosion crust shown in the Backscattered Electron images, the spectrometer analyzed the emitted X-rays to identify the elemental makeup of the sample at that exact location. The resulting spectral graphs were highly revealing from an agronomic perspective. As chemically expected, the spectra showed towering concentrations of zinc, iron, oxygen, and carbon, representing the oxidized remains of the original coating and the base steel. However, the critical findings that solved the failure mechanism were the distinct and prominent spectral peaks corresponding to external elements.

The Energy Dispersive X-ray spectra consistently and repeatedly identified the presence of nitrogen, phosphorus, potassium, sulfur, calcium, sodium, and silicon embedded deep within the metallic corrosion matrix. The presence of silicon, calcium, and sodium can be easily attributed to the natural mineralogical composition of the surrounding clay soil physically adhering to the porous rust. Crucially, however, the highly significant weight percentages of nitrogen, phosphorus, and potassium provide direct, forensic proof of fertilizer-induced corrosion. These specific elements do not naturally occur in such high concentrations within pure metallic corrosion layers. Their deep integration into the rust matrix demonstrates unequivocally that the dissolved NPK fertilizers did not merely increase the conductivity of the soil water from a distance; they actively participated in the electrochemical dissolution process directly at the metal-electrolyte interface. The dissolved fertilizer salts physically permeated the porous zinc oxides, completely preventing the layer from passivating and sealing the surface, thereby keeping the sacrificial metal in a state of perpetual, active dissolution until it was entirely depleted.

Based on the chronological data of the installation and the physical evidence gathered through microscopy, the actual corrosion rates can be extrapolated, painting a severe picture of the agricultural environment's true aggressiveness. The initial zinc-aluminum-magnesium coating possessed a theoretical uniform thickness of 25 μm . Because the Backscattered Electron images undeniably show that this entire layer was

transformed into non-protective corrosion products within a maximum of three years, the minimum uniform corrosion rate of the coating must have mathematically exceeded $8.3 \mu\text{m}$ per year. This dissolution rate is exceptionally high for an advanced ternary alloy that typically loses less than a single μm per year in standard atmospheric conditions, highlighting the devastating impact of the soil burial [34].

Once this sacrificial coating was inevitably breached, the electrochemical attack concentrated entirely on the structural carbon steel core. The theoretical DIN 50929-3 calculation predicted a generalized steel corrosion rate of $60 \mu\text{m}$ per year. However, the morphology of the attack observed under the electron microscope and visually on the pole was absolutely not purely uniform. Despite the relatively short operational timeframe of thirty-six months, the microscopic cross-sections revealed highly irregular, deep penetrations gouging into the steel substrate, which is the classic characteristic signature of pitting corrosion. The standard had accurately predicted that localized pitting in this specific low-resistivity, clay-heavy environment could reach catastrophic velocities up to $400 \mu\text{m}$ per year. This highly localized mechanism is powerfully driven by the differential aeration cell formed along the length of the pole, vastly exacerbated by the patchy, uneven accumulation of wet, dense clay clods physically pressing against the steel surface. These clods create small, intensely anodic areas that are starved of oxygen, relative to adjacent, slightly more aerated micro-zones. Furthermore, the detected presence of copper residues originating from standard vineyard fungicides in the soil provides the electrochemical potential for micro-galvanic displacement reactions directly on the zinc surface, further nucleating deep, rapid pits that accelerate structural failure [21].

In conclusion, the detailed comparative analysis of the failed vineyard poles provides an unequivocal, real-world validation of the severe corrosion risks faced by agrivoltaic foundations. The study conclusively demonstrates that relying solely on the inherent atmospheric durability of advanced zinc-aluminum-magnesium coatings, or predicting the foundation lifespan based on standard, non-agricultural soil resistivity measurements, is a fundamentally flawed engineering approach. The continuous application of agrochemical fertilizers radically and permanently alters the telluric electrolyte, transforming a potentially benign clay into a highly conductive, chemically aggressive medium. The devastating combination of extremely low resistivity induced by nitrates and phosphates, poor telluric aeration caused by the dense clay matrix, and the resulting macroscopic differential aeration cells leads to the rapid depletion of thin sacrificial coatings and the subsequent aggressive pitting of the primary structural steel. This failure mechanism occurs precisely at the air-soil transition zone, which coincidentally represents the most mechanically stressed point of the solar tracker under wind loading. Therefore, the implementation of supplementary passive protection strategies, such as heavy bituminous sheaths, robust polymer collars, or complete concrete encasement at the ground level interface, is not merely a theoretical

recommendation but an absolute practical necessity to guarantee the structural survival of the agrivoltaic plant over its required 30 year design life [15].

6.3. Model preparation and comparison

The ultimate intention of this research is to provide a reliable predictive model capable of estimating the corrosion rate of protective galvanization and the underlying base steel, including weathering variants like Corten, in underground applications. To be practically applicable during the engineering phase of solar structures, this model must express the anticipated structural decay as a mathematical function of the primary environmental parameters derived from literature and normative standards. Extensive geotechnical studies have identified the hydrogen-ion concentration, the specific electrical conductivity, the permanent or cyclical presence of telluric water, and the mechanical composition of the soil matrix as the absolute fundamental drivers of the electrochemical degradation process [19].

Constructing such a prediction model from scratch presents significant logistical and methodological challenges. There is a severely limited capacity to retrieve all this necessary information from existing, operational photovoltaic plants. Plant owners are contrary to permit the dismantling of some foundation piles for inspection, and correlating the exact historical chemical data of the soil with the specific pile is often impossible due to the lack of preliminary geochemical surveys at the time of construction. In virtue of these difficulties, it is necessary to describe how to structure the model to follow a standardized, highly rigorous method of data collection. This ensures that the methodology can be seamlessly replicated in future analyses, gradually expanding the empirical database.

The structural basis of the proposed model relies on establishing a theoretical baseline utilizing historical empirical data and current normative standards. The reference values extracted from the National Bureau of Standards investigations conducted by Romanoff, alongside the theoretical design allowances prescribed by the European standard EN 1993-5, serve as the initial coordinates for the predictive curves.

To build the practical side of the model, the terrain must be sampled according to the standardized methodologies prescribed previously. The soil extraction must occur exactly at the air-soil transition zone of the investigated pile to guarantee a direct spatial correlation between the chemical aggressiveness of the measured electrolyte and the localized physical degradation observed on the metal. Subsequently, the decay rate must be recorded by strictly distinguishing the years elapsed before extraction. As demonstrated by historical field tests, the model must mathematically account for the non-linear progression of underground corrosion. The velocity of the attack is invariably higher during the first years of burial, when the pristine metal is suddenly exposed to moisture and oxygen, while a progressive stabilization occurs in the long

term due to the accumulation of insoluble corrosion products that partially suffocate the reaction [19].

To systematically evaluate the progression of corrosion over time and establish a reliable empirical baseline, an in-depth analysis of the extensive field investigations conducted by Melvin Romanoff at the National Bureau of Standards was performed. This historical dataset represents a fundamental pillar in the study of underground corrosion, providing essential numerical values for the degradation of metallic structures across a wide variety of soil environments. The data extracted from this study have been organized to distinguish the initial aggressive attack from the long-term stabilization [19].

The following tables present the empirical results extracted and converted from the National Bureau of Standards long-term corrosion tests and the study of [19]. To allow a direct comparison of the temporal evolution, data for two distinct extraction periods are reported for each site: the early years of burial (approximately 2 years) and the long-term extraction (between 12 and 14 years).

The conversion factors used to transition from the imperial to the metric system are as follows: for pit depth, 1 mil equals $25.4\ \mu\text{m}$; for material consumption, 1 ounce per square foot is equivalent to $35.56\ \mu\text{m}$ of thickness for carbon steel and $43.69\ \mu\text{m}$ for zinc [72]. The original thickness of the steel pipe (1.5 inches) is approximately $3683\ \mu\text{m}$, while the nominal hot-dip galvanized coating (3.08 ounces per square foot) corresponds to an average of $135\ \mu\text{m}$ [19]. In cases where the weight loss of the galvanized sample exceeds the mass of the coating alone, the consumed material includes the original $135\ \mu\text{m}$ of zinc plus the equivalent volumetric portion of consumed structural steel.

To establish the historical benchmark for the model, a specific numerical averaging of the data previously extracted from the Romanoff tables has been calculated. Taking into consideration all soil types from the dataset where both bare carbon steel and hot-dip galvanized steel were simultaneously tested, the average values provide a macroscopic reference point for general underground behavior.

Table 11 – Average corrosion rates, R , of galvanized steel pipe specimens^b embedded in various soils for 10 years^a [72]

No. ^c	Soil type	ρ (Ω -cm)	pH	R (μ m/yr)
1	Allis silt loam, Cleveland, Ohio	1,215	7.0	11.8
2	Bell clay, Dallas, Tex.	684	7.3	1.5
3	Cecil clay loam, Atlanta, Ga.	30,000	5.2	1.7
4	Chester loam, Jenkintown, Pa.	6,670	5.6	7.9
5	Dublin clay adobe, Oakland, Calif.	1,345	7.0	7.7
6	Everett gravelly sandy loam, Seattle, Wash.	45,100	5.9	0.5
7	Maddox silt loam, Cincinnati, Ohio	2,120	4.4	10.8
8	Fargo clay loam, Fargo, N. Dak.	350	7.6	3.2
9	Genesee silt loam, Sidney, Ohio	2,820	6.8	5.0
10	Gloucester sandy loam, Middleboro, Mass.	7,460	6.6	5.2
11	Hagerstown loam, Loch Raven, Md.	11,000	5.3	3.7
12	Hanford fine sandy loam, Los Angeles, Calif.	3,190	7.1	2.2 ^d
13	Hanford very fine sandy loam, Bakersfield, Calif.	290	9.5	3.7
14	Hempstead silt loam, St. Paul, Minn.	3,520	6.2	1.1
15	Houston black clay, San Antonio, Tex.	489	7.5	1.5
16	Kalmia fine sandy loam, Mobile, Ala.	8,290	4.4	4.2
17	Keyport loam, Alexandria, Va.	5,980	4.5	14.8 ^e
19	Lindley silt loam, Des Moines, Iowa	1,970	4.6	2.9
20	Mahoning silt loam, Cleveland, Ohio	2,870	7.5	4.9
22	Memphis silt loam, Memphis, Tenn.	5,150	4.9	5.2
23	Merced silt loam, Buttonwillow, Calif.	278	9.4	40.6 ^e
24	Merrimac gravelly sandy loam, Norwood, Mass.	11,400	4.5	1.1
25	Miami clay loam, Milwaukee, Wis.	1,780	7.2	1.45
26	Miami silt loam, Springfield, Ohio	2,980	7.3	2.9
27	Miller clay, Bunkie, La.	570	6.6	3.9
28	Montezuma clay adobe, San Diego, Calif.	408	6.8	8.8
29	Muck, New Orleans, La.	1,270	4.2	25.5 ^e
30	Muscatine silt loam, Davenport, Iowa	1,300	7.0	1.9
31	Norfolk fine sand, Jacksonville, Fla.	20,500	4.7	0.67
32	Ontario loam, Rochester, N.Y.	5,700	7.3	2.4
33	Peat, Milwaukee, Wis.	800	6.8	7.4
35	Ramona loam, Los Angeles, Calif.	2,060	7.3	1.3
36	Ruston sandy loam, Meridian, Miss.	11,200	4.5	1.0
37	St. John's fine sand, Jacksonville, Fla.	11,200	3.8	8.7
38	Sassafras gravelly sandy loam, Camden, N.Y.	38,600	4.5	0.85
40	Sharkey clay, New Orleans, La.	970	6.0	4.0
41	Summit silt loam, Kansas City, Mo.	1,320	5.5	2.2
42	Susquehanna clay, Meridian, Miss.	13,700	4.7	3.0
43	Tidal marsh, Elizabeth, N.J.	60	3.1	5.5
44	Wabash silt loam, Omaha, Nebr.	1,000	5.8	1.9 ^d
45	Unidentified alkali soil, Casper, Wyo.	263	7.4	7.5
46	Unidentified sandy loam, Denver, Colo.	1,500	7.0	0.7
47	Unidentified silt loam, Salt Lake City, Utah	1,770	7.6	4.3

^aAverage coating thickness, 121 μ m.^bRef. 357.^cOriginal identification.^dSheet specimens.^eCoating corroded completely; data included the corrosion of steel.

Table 12 - Average annual surface-averaged corrosion rates (CR) and maximum penetration rates (MPR) of zinc and galvanized steel embedded in soils for 9 years^a [72]

No. ^b	Soil type	ρ (Ω -cm)	pH	Rolled zinc		Galvanized steel ^c		Steel	
				CR (μ m/yr)	MPR (μ m/yr)	CR (μ m/yr)	MPR (μ m/yr)	CR (μ m/yr)	MPR (μ m/yr)
51	Acadia clay	190	6.2	22.9	79	22.9	22.5	83	361+
53	Cecil clay loam	17,790	4.8	5.3	36.6	3.8	16.9	16.2	209
55	Hagerstown loam	5,210	5.8	3.3	22.5	3.9	16.9	19.6	260
56	Lake Charles clay	406	7.1	21.5	81.8	26.3	36.7	132	409+
58	Muck	712	4.8	35.3	163	43	180.6	82.7	277
59	Carlisle muck	1,660	5.6	21.9	61.1	14.1	22.2	35.8 ^d	56.4
60	Rifle peat	218	2.6	112 ^d	416+	77.4 ^d	234+	85.5	164
61	Sharkey clay	943	6.8	5.2	39.5	7.2 ^d	34	20.1	135
62	Susquehanna clay	6,920	4.5	6.2	33.9	4.3	16.9	25.3	192
63	Tidal marsh	84	6.9	9.6	69.4	9.6	22.6	51.1	226
64	Docas clay	62	7.5	6.7	223	7.6	28.2	43 ^d	226
65	Chino silt loam	148	8.0	6.7	158	7.6	16.9	33.4	183
66	Mohave fine gravelly loam	232	8.0	28 ^d	124	11.9	16.9	58.8 ^d	409+
67	Cinders	455	7.6	131 ^d	749+	58	286	151	409+
70	Merced silt loam	278	9.4	17.2	237	9.9 ^e	18.5	64	344

^aRef 357.^bIdentification in the original report.^cNominal coating thickness, 130 μ m.^dData at 4 years.^eData at 11.2 years.

For bare carbon steel, the calculated average uniform corrosion rate during the initial two years of exposure stands at 98.2 μ m per year. In the long-term evaluation, spanning twelve to fourteen years, this average uniform rate drops to 67.0 μ m per year, demonstrating the anticipated stabilization. However, analyzing the maximum pit depth reveals the true destructive potential of the soil; the initial average pitting rate reaches an extreme 750.7 μ m per year, which then settles to a long-term average pitting rate of 192.7 μ m per year.

For hot-dip galvanized steel, featuring an original theoretical zinc thickness of 121, the calculated average uniform consumption of the coating, excluding the first and last 5% value (to eliminate outlier data) is 5.3 μ m per year. The pitting phenomena on the galvanized samples show a long-term average pitting rate of 64.7 μ m per year. These specific numerical averages represent the historical reference values against which any new empirical model must be calibrated [19], [72].

Following the establishment of this historical baseline, the model must be compared with the current regulatory framework. The standard EN 1993-5 dictates the design parameters for steel piling and provides specific tables for the loss of thickness due to corrosion in soils. According to the normative guidelines, the corrosion rates of bare steel given should be considered as calculative values for design only, assuming a strictly mean uniform corrosion without considering potential localized pitting [73]. For a required design service life of twenty-five years, the standard estimates a total thickness loss of 0.30 mm in undisturbed natural soils, 0.75 mm in polluted natural

soils and industrial sites, and 1.00 mm in aggressive natural soils like swamps and marshes [73].

When these normative 25-year allowances are converted into annual rates to match the model's parameters, they translate to 12 μm per year for undisturbed soils, 30 μm per year for polluted soils, and 40 μm per year for aggressive soils. Comparing these theoretical normative rates with the long-term historical averages extracted from Romanoff, which sit at 67 μm per year for uniform bare steel corrosion, reveals a significant discrepancy. The EN 1993-5 estimates appear highly conservative or presume perfectly compacted, low-oxygen telluric environments.

Considering this discrepancy, along with the different measurement techniques utilized in the past, the vast specificities of local soil typologies, the metallurgical evolution of structural steel over the last century, and above all, the completely different operational context introduced by agrivoltaics, relying solely on old databases and theoretical norms is insufficient. The continuous manipulation of the agricultural soil, the massive introduction of artificial fertilizers that lower resistivity, and the artificial irrigation cycles create a unique electrochemical reactor that neither Romanoff nor the Eurocode 3 specifically addressed. Therefore, it is considered fundamentally important to perform new, highly specific measurements on actual photovoltaic and agrivoltaic sites to create a completely new, modern database.

This new database will allow engineers to directly compare the contemporary field behavior of the materials with the technical normative references and the historical Romanoff curves, effectively validating or modifying the predictive model for the specific agrivoltaic sector. However, the limitation of acquiring specimens from active solar plants remains.

To overcome this, the most effective and exhaustive method proposed to feed data in the new predictive model is to systematically exploit the inspection on revamping processes of mature photovoltaic installations. Revamping involves the complete decommissioning and replacement of older solar structures to install modern, higher-yield trackers or panels. During this heavy engineering phase, thousands of foundation piles that have been buried for ten to fifteen years are mechanically extracted from the ground and destined for scrap.

This scenario provides a massive, unprecedented availability of real-world test specimens. Since it is impossible to know the exact original pre-driving weight of these commercial profiles, the weight-loss evaluation methods utilized in early 20th-century laboratory tests are inapplicable. Instead, the extracted piles must be subjected to precision laboratory measurements focusing on the residual thickness. By sectioning the pile at the exact air-soil transition mark, carefully removing the adhered agricultural soil for parallel DIN 50929-3 chemical analysis, and cleaning the surface with non-destructive chemical baths, researchers can utilize advanced ultrasonic

thickness gauges and microscopic metallography to determine the exact remaining cross-section of the steel and any residual traces of the zinc-iron alloy layers.

Subtracting this measured residual thickness from the nominal manufacturing thickness of the specific profile yields the absolute material loss. Dividing this loss by the known operational lifespan of the revamped plant provides a highly accurate, real-world uniform corrosion rate and a specific localized pitting rate. By collecting these samples across various revamping sites characterized by different agricultural uses and soil conductivities, the predictive model can be continuously updated. This methodology bypasses the limitations of short-term laboratory simulations, directly anchoring the prediction of future agrivoltaic foundation lifespans to the actual, measured degradation kinetics occurring in modern agricultural soils.

7 Chapter 7: conclusions and future developments

7.1. Summary of main results

The progressive transition from traditional ground-mounted photovoltaic installations to integrated agrivoltaic systems represents a paradigm shift in renewable energy engineering. This thesis has systematically investigated the intersection of mechanical structural design, materials science, and agronomy, aiming to define and mitigate the severe corrosive phenomena that threaten the durability of solar tracking foundations. Based on the extensive theoretical analysis, the normative review, and the experimental field campaign conducted, this concluding chapter synthesizes the fundamental steps of the research and outlines the main results achieved.

One of the first and most critical findings of this research is the definitive confirmation that the agrivoltaic environment is significantly more aggressive than the context of traditional photovoltaics. In standard solar parks, the supporting structures are typically driven into undisturbed, compacted, and often sterile or marginal soils [3]. In stark contrast, agrivoltaic foundations are immersed in a dynamic, artificially modified biochemical reactor. The continuous implementation of specific agricultural practices, primarily artificial irrigation cycles, massive fertilization, the application of pesticides, and the periodic mechanical tillage of the superficial soil, drastically alters the electrochemical boundary conditions.

The investigation clearly identified the topsoil layer, specifically the first 50 cm representing the air-soil transition zone, as the most critically stressed sector of the entire structural framework. In this specific shallow band, the mechanical tilling maximizes soil aeration, while irrigation creates continuous wet and dry cycles. This combination generates a highly powerful differential aeration macrocell, where the oxygen-starved buried steel becomes the active anode and dissolves rapidly [42]. Furthermore, this top layer acts as a sponge for agrochemicals. The accumulation of nitrogenous fertilizers, which cause biological acidification through nitrification, and the presence of highly conductive sulfates and chlorides from pesticides, drastically drop the electrical resistivity of the pore water. These combined agricultural factors generate an environmental context that is unequivocally more burdensome and destructive than any sterile industrial site traditionally evaluated in solar engineering.

In response to this severe environmental stress, the research heavily evaluated the materials utilized for structural protection, leading to significant conclusions regarding galvanization technologies. Currently, the vast majority of photovoltaic structures rely on traditional batch hot-dip galvanizing. However, the analysis highlighted the extraordinary innovation brought by ternary zinc-aluminum-magnesium alloys. Despite their proven electrochemical superiority, these advanced alloys are still adopted only in a minimal part for agrivoltaic structures today [32].

The extensive adoption of zinc-aluminum-magnesium coatings would bring a twofold structural and economic benefit. For the aerial portion of the structure exposed to the agricultural atmosphere, these alloys provide superior barrier protection and a self-healing effect on cut edges, requiring a significantly minor thickness compared to traditional hot-dip galvanization to achieve the same design life [33]. More importantly, for the buried portion of the foundation, the zinc-aluminum-magnesium alloys exhibit a much better response in the telluric context compared to pure zinc. The magnesium facilitates the precipitation of stable, insoluble hydroxides that are incredibly resilient to the sudden pH drops caused by ammonia and fertilizers [32]. Transitioning to these advanced continuous coatings would therefore lead to substantial cost savings for equal structural protection and a significant speeding up of the manufacturing process, as it eliminates the need for post-fabrication batch dipping.

Parallel to the study of zinc coatings, the research addressed the complex integration of weathering steel, commercially known as Corten. Corten is an alloy that could potentially gain widespread acceptance in the agrivoltaic sector, particularly due to its aesthetic chromatic integration, which satisfies the stringent landscape regulations often imposed on rural installations [36]. However, the results underline severe risks associated with its use in the soil environment. The primary vulnerability is tied to the risk of failing to develop the protective oxyhydroxide patina before the pile is driven into the ground. Because Corten requires alternating wet and dry cycles and abundant oxygen to passivate, burying it directly into the constantly moist, oxygen-deprived, and fertilizer-rich agricultural soil prevents the patina from forming [35]. Consequently, the buried Corten behaves similarly to unalloyed carbon steel, suffering rapid and aggressive localized pitting. Therefore, despite its visual appeal, its application carries many uncertainties and requires strict engineering precautions, such as the use of protective concrete collars with proper drainage drafts at the ground interface.

A cardinal aspect of this entire research has been the application of a rigorous quantitative approach, based on the comparative analysis of several international technical standards. The investigation specifically dissected the atmospheric corrosivity standard ISO 9223, the steel piling design guidelines of EN 1993-5, the

general soil corrosivity likelihood matrix of ISO 12501, and the highly detailed German standard DIN 50929-3 [38], [46], [63].

The critical review of these norms revealed that the DIN 50929-3 standard is vastly superior for the agrivoltaic context, as it takes into consideration the greatest number of empirical values and chemical agents to classify the corrosion load accurately [46]. By integrating the multifactorial logic of the DIN standard with a simplified field methodology, this research demonstrated that it would be possible to create a predictive model for the corrosion rate specifically tailored to the photovoltaic context. By eliminating further extraneous environmental variables and focusing strictly on the measurable chemical inputs of the specific agricultural site, this predictive model could become particularly accurate, potentially reaching a precision in the order of 1-2 μm per year. Achieving this level of predictive accuracy would significantly reduce the capital costs associated with over-dimensioning the steel thicknesses while simultaneously increasing the safety and durability guarantees of the plants.

The experimental data collected during the field campaigns provided vital numerical validation for these theoretical models. The physical measurements of residual coating thicknesses recorded across the investigated sites indicate an average corrosion rate hovering around 5 μm per year for the galvanized steel foundations operating in active agricultural soils. This specific empirical parameter is extraordinarily significant when compared to the historical geotechnical data. It aligns with the historical rate studied by Melvin Romanoff during his monumental underground corrosion investigations, which identified an average consumption of 5.34 μm per year for galvanized steel, provided that the 5 % of extreme values both at the upper and lower ends of the statistical distribution are excluded [19]. It is worth noting that if those extreme values (representing highly acidic, zinc depletion or perfectly sterile soils) were included, the historical average would shift to 7.13 μm per year. While the 4 - 5 μm per year rate estimate in this thesis is remarkably similar to Romanoff's adjusted baseline, it must be stated that it is not yet perfectly comparable due to the lack of a sufficient quantity of long-term data specifically extracted from mature agrivoltaic plants over multiple decades.

To bridge this data gap and validate the aggressive nature of the agricultural inputs, a particularly relevant section of the research relied on the similitude with vineyard posts. The comparative analysis of vineyard poles, which share the exact same structural profiles, protective coatings, and soil environment as agrivoltaic piles, proved to be highly revealing. The severe structural failures actually observed on these posts provided undeniable forensic proof of the devastating effects of fertilizers [21]. The deep integration of nitrogen, phosphorus, and potassium into the corrosion crust of the failed poles definitively links the structural degradation to agronomic practices. This specific correlation makes the present study one of the first explicit examples of

direct correlation between these agricultural problems and the durability of solar tracking infrastructure.

Finally, recognizing that comprehensive DIN-compliant laboratory analyses are often economically unviable for small-scale solar developers, a major practical outcome of this work is the proposition of a simplified field procedure. As described in the methodology chapters, this simplified procedure utilizes portable multiparameter probes to measure the electrical conductivity, pH, and redox potential of a moist soil extract directly on-site [51]. If this procedure is adopted, it allows operators to verify the conditions of the terrain in an economical and highly rapid manner. It serves as a highly effective screening method to anticipate whether a more profound and rigorous geochemical analysis is required. Given that deep laboratory analyses are often not realizable for budget reasons on small plants, this simplified protocol empowers maintenance technicians to detect dangerous spikes in soil aggressiveness caused by farming practices, ensuring that predictive maintenance can be executed efficiently to protect the long-term viability of the renewable energy asset.

7.2. Original contribution in AGV sector

The recent legislative and market dynamics across Europe have triggered a massive boom in the development of agrivoltaic projects, which are increasingly favored over traditional ground-mounted photovoltaic plants. Driven by ambitious national recovery plans and stringent decarbonization targets, the energy sector is rapidly occupying agricultural lands. However, this transition is often approached with a conventional photovoltaic mindset, treating the agricultural soil merely as a physical support rather than a dynamic, chemically active ecosystem. Within this rapidly evolving scenario, this work positions itself as an innovative and deeply relevant perspective aimed at fundamentally improving engineering design techniques. The primary objective is to bridge the gap between structural engineering and agronomy, providing a framework to prevent the premature loss of value of the solar plant and to proactively avoid the necessity of subsequent, highly expensive structural replacement interventions.

It is absolutely crucial to maintain a high level of technical scrutiny when combining photovoltaic systems with traditional, intensive agriculture. This specific context extends far beyond the simple, passive pastoral grazing meadows that characterized early dual-use solar parks. Modern agrivoltaic systems are integrated into intensive crop production, which involves the systematic application of advanced irrigation techniques, aggressive fertigation cycles, and the use of chemical pesticides and herbicides. The inherent danger of combining steel foundations with this chemically altered environment has been clearly demonstrated in the previous comparative analyses. The rapid structural failures observed in the vineyard posts case study,

alongside the severe degradation documented in the intensive greenhouse installations in Almería, serve as undeniable proof that agricultural practices drastically accelerate corrosion kinetics [74]. In these environments, the continuous modification of the telluric electrolyte through farming practices transforms a potentially benign soil into a highly conductive and corrosive medium.

The agrivoltaic context is a delicate balance that must be protected and monitored to understand not only the structural impacts but also the effects of shading on agricultural yield. Current national guidelines and technical rules formally require the installation of dedicated monitoring stations to ensure that the agricultural activity is not compromised by the solar infrastructure. According to these regulatory frameworks, these monitoring stations typically measure standard meteorological and soil parameters, including air and soil temperature, relative humidity, wind speed, and solar irradiation [4]. While these parameters are fundamental for assessing the microclimate and crop evapotranspiration, this work argues that they are insufficient for a complete systemic overview.

As contribution of this research suggests that these mandatory monitoring systems should be significantly expanded. By integrating the continuous measurement of specific geochemical parameters such as soil pH, electrical conductivity, and the concentrations of dissolved fertilizers expressed as nitrogen, phosphorus, and potassium macro-elements, it is possible to perform a much more accurate verification of the site. This integration transforms the simple coexistence of solar panels and crops into a mutually beneficial relationship, effectively pushing the industry toward a true format of agriculture 4.0. In this advanced technological paradigm, the real-time verification of chemical parameters provides a vital dual benefit. On one hand, it allows agronomists to optimize crop yield, minimize fertilizer waste, and manage water resources efficiently. On the other hand, it provides corrosion engineers with the exact environmental boundary conditions necessary to monitor the health status of the metallic support structures, enabling accurate predictive maintenance models based on actual soil resistivity and acidity.

Going into further detail, this thesis represents a first, foundational approach to verifying the corrosive impact of the active principles utilized in modern fertilizers on steel foundations. It highlights the urgent need for a deeper academic investigation from the agronomic side to fully comprehend the nuances of this interdisciplinary theme. What has been consistently found during this research is a particularly harmful interaction between metallic foundations and specific agricultural drivers. These include intense microbiological activity, the accumulation of sulfides and sulfur derivatives, and the massive application of ammonia-based compounds that are expressly designed to actively modify the soil pH.

In intensive agriculture, manipulating the soil pH is a standard practice to maximize the bioavailability of nutrients for specific crops. However, an agronomic target of a

more acidic pH represents the most dangerous boundary condition for the foundations. Acidic environments rapidly consume the amphoteric zinc coatings and prevent the formation of the protective oxyhydroxide patina on Corten steel [15]. This means that the very practices required to ensure a successful harvest are fundamentally at odds with the survival of the steel structures supporting the solar panels.

Consequently, the selection of the plant species to be cultivated beneath an agrivoltaic system must be evaluated with extreme attention, incorporating materials science into the agronomic business plan. The industry must move towards tailoring the best solutions for integration, rather than forcing the principle that every type of terrain and every single crop must necessarily be combined with solar production. Agrivoltaic systems should be dedicated exclusively to those sites and crops that demonstrate the highest degree of both biological and structural compatibility. For instance, crops that require highly acidic soils or continuous, heavy localized fertigation should perhaps be avoided in favor of crops that thrive in neutral pH environments with lower chemical inputs, thereby protecting the underlying investment [3].

Furthermore, a critical note must be made regarding the widespread perception of organic farming. Within public and sometimes technical discourse, there is a frequent misconception that organic agriculture is inherently safer, gentler, or less aggressive than conventional, chemistry-intensive farming. However, from a corrosion engineering standpoint, this is a dangerous fallacy. It is not solely the synthetic or artificial nature of chemical agents that is problematic for the metallic structure, but rather the active chemical principles themselves. Organic farming relies heavily on natural inputs that can be devastating to metals. The use of raw animal manure introduces massive amounts of ammonia and accelerates anaerobic bacterial activity. The application of elemental sulfur to control fungal diseases in organic vineyards drastically lowers the soil pH. The use of copper-based fungicides, permitted in organic agriculture, introduces noble metal ions into the soil that can trigger severe galvanic displacement reactions with the zinc coatings. Therefore, the level of engineering attention, the thickness of the sacrificial coatings, and the implementation of passive barrier protections must not be lowered in the case of organic crop cultivation. The structural design must respect the chemistry of the soil, regardless of whether the inputs are classified as synthetic or organic.

7.3. Mitigation strategies (engineering proposals)

7.3.1. Passive protection at the interface

The structural vulnerability of a driven foundation pile is not distributed uniformly along its entire length. Instead, it is dramatically concentrated in an extremely narrow altimetric band known as the air-soil transition zone, or splash zone. This critical area typically extends from 30 cm above the ground level to 50 cm below it. In this restricted spatial segment, the most severe triggering factors for wet corrosion converge. The predominant electrochemical mechanism governing this band is the constitution of a differential aeration macro-cell. The portion of the steel immediately below the ground level, which is constantly wetted by capillary moisture but deprived of free oxygen compared to the emerged portion, assumes a strongly anodic potential. This oxygen concentration gradient drives a localized galvanic current that forces the rapid dissolution of the metallic coating and the underlying carbon steel, generating a severe corrosive ring exactly where the bending moment generated by wind loads reaches its maximum structural value [15].

In the specific case of piles embedded in concrete foundation plinths or micropiles, the maximum vulnerability shifts precisely to the interface between the extrados of the concrete and the emerging steel. Water stagnation at this specific contact point triggers carbonation processes and sulfate attacks that destroy the passivating alkalinity of the cement, creating micro-cracks that act as incubators for chlorides and acidic moisture. This phenomenon accelerates the formation of a corrosion ring. To overcome these pathologies, corrosion engineering prescribes the implementation of passive barriers, which are dielectric coating systems designed to waterproof the interface, physically excluding the electrolyte and oxygen from the metallic surface and effectively deactivating the galvanic macro-cell [18].



Figure 37 – Bituminous protection of illumination pole

The necessity to protect the ground line of metallic supports boasts a wide historical case study in civil infrastructure engineering, particularly in the public lighting and road sign sectors. Historically, the passive protection par excellence for circular lighting poles was represented by the application of hot-applied bituminous bands. Bitumen offers extraordinary hydrophobic properties and excellent chemical tolerance in both acidic and alkaline environments, isolating the metal from interstitial soil water. However, traditional bituminous coatings maintain a degree of plasticity that makes them highly susceptible to mechanical damage from impact or abrasion during the brutal operations of hydraulic ramming typical of solar construction. A single tear in the bituminous mantle concentrates the entire anodic current of the macro-cell in that small defect, triggering penetrating pitting at extreme speeds [15].



Figure 38 - shrinkable anticorrosive sleeves

To overcome the rheological and mechanical limits of liquid bituminous compounds, modern engineering has shifted the standard towards the use of prefabricated heat-shrinkable anticorrosive sleeves. These devices are extruded using high-thickness cross-linked polyolefins. The cross-linking process creates three-dimensional covalent bonds between the polymer chains, granting the material a thermomechanical shape memory, exceptional tensile strength, resistance to gravel abrasion, and superior tolerance to ultraviolet rays for the portion exposed to the air. The absolute effectiveness of these passive barrier systems is intrinsically linked to the cross-sectional geometry of the foundation pile. On a circular tubular profile, the thermodynamics of polymer shrinkage work in perfect harmony with the geometry. The shrinkage generates purely radial and perfectly symmetrical force vectors along the entire circumference. The pressure applied to the hot-melt mastic adhesive is constant at every point, ensuring a uniform squeeze that hermetically seals the transition without any risk of delamination [75].

Conversely, applying standard tubular sleeves on cold-formed open profiles, such as C-sections or Ω -sections, introduces severe morphological incompatibilities resulting in a bridging effect. The polymer shrinks linearly between the outer edges of the profile, completely ignoring the internal concavities and creating macroscopic

longitudinal voids. These hidden cavities act as perfect incubators for anoxic moisture and anaerobic bacteria, such as sulfate-reducing bacteria, accelerating the pitting rate exponentially. Therefore, for open profiles, the application of heat-shrinkable sleeves requires attention and is not the recommended solution strategy [75].

In complex structural nodes or on open profiles where the application of solid sleeves and butyl fillers is uneconomical or impractical, the passive protection strategy must rely on high-performance liquid paint coating systems. The design and validation of these organic systems are strictly regulated by the EN ISO 12944 standard. According to this standard, the pile of an agrivoltaic tracker simultaneously crosses two extreme corrosive domains. The buried portion falls into the Im3 immersion category, designating structures buried in soil, while the emerged transition zone falls into the C3 atmospheric categories due to the high humidity from evapotranspiration and the deposition of chemical aerosols from fertigation. To achieve a very high durability of over twenty-five years, the standard prescribes multi-coat systems based on high-build epoxy primers and aliphatic polyurethane topcoats. The epoxy-polyamide primer provides excellent water impermeability and resistance to alkaline hydrolysis, while the aliphatic polyurethane topcoat provides absolute stability against ultraviolet radiation and exceptional elastic toughness to resist the destructive impact of gravel raised by agricultural machinery [44].

However, the geometric shape of the profile drastically influences the fluid dynamics of the liquid paint and its ultimate protective effectiveness. C-shaped profiles present partially closed sections with re-entrant angles and sharp outer edges. During the application of a liquid polyurethane paint, the surface tension causes the liquid to pull away from the sharp external edges before curing, leaving minimal dry film thicknesses highly vulnerable to early rust. Inside the re-entrant corners, the paint spray suffers from a Faraday cage effect, leaving shadowed areas where the spray trajectory cannot reach. To compensate for these intrinsic limits, EN ISO 12944 requires rigorous design measures. It demands the mechanical chamfering of sharp edges to a specific radius and the mandatory manual application of a stripe coat using a brush on all lips and internal corners prior to the general airless spray. This requirement heavily impacts the logistics and costs of prefabrication [75].

On the contrary, adopting an entirely open profile such as the Ω shape provides significant technical advantages for paint applications. The Ω profile lacks re-entrant lips. This open geometry completely eliminates the spray shadowing effect and minimizes the surface tension issues on the edges. The polyurethane paint can easily wet all surfaces, allowing for highly uniform coverage and consistent dry film thickness during the automated spraying process without the strict necessity of intensive manual stripe coating [15].

A special analytical mention within passive protection is dedicated to the geotechnical management of weathering steel, commonly known as Corten. Due to aesthetic and

landscape regulations, Corten is frequently utilized in rural agrivoltaic parks. Corten develops its immunity to atmospheric corrosion through a thermodynamic self-passivation mechanism, forming a protective patina of amorphous oxyhydroxides. However, this patina strictly requires alternating cycles of wetting and complete drying combined with abundant oxygen. When Corten is driven directly into wet, anoxic agricultural soil, this fundamental requirement fails completely, and the material suffers catastrophic localized pitting exacerbated by the acidic fertilizers [36].

To mitigate this failure, a hybrid engineering approach is required: the underground portion of the Corten pile must be entirely segregated within a foundation collar cast in concrete. The hydration of Portland cement guarantees a permanently alkaline interstitial solution with a pH between 12.5 and 13.5. In this ultra-alkaline range, the thermodynamics of iron shift into a regime of absolute passivity. The embedded Corten steel reacts almost instantly, forming a microscopic passive film of dense ferric oxides that suffocates the anodic dissolution process to virtually zero. Furthermore, the diffusion of hydroxyl ions from the concrete positively influences the area immediately above the interface[19].

The crucial engineering element to make this concrete collar safe is the mandatory implementation of a steep geometric draft for water drainage on the upper surface. The concrete plinth must emerge above ground level and its top surface must taper downwards away from the steel profile. This watershed design uses gravity to instantly evacuate rainwater and fertilizer percolates. By preventing water stagnation, it avoids the carbonation of the concrete and the destructive expansion of secondary ettringite caused by agricultural sulfates. Because the drafted collar keeps this critical interface dry, the Corten steel situated just above the concrete benefits from the alkaline influence and can properly undergo its necessary dry-wet cycles, successfully forming its protective patina exactly at the most vulnerable ring [36].

It is also critical to strictly avoid any direct electrical contact between Corten steel and galvanized components within this foundation node. According to the galvanic series, zinc is highly anodic compared to the noble Corten alloy. In the presence of the conductive agricultural electrolyte, this bimetallic coupling triggers a violent galvanic cell where the zinc coating is rapidly consumed to protect the Corten, leading to the premature structural failure of any adjacent galvanized elements. Therefore, proper dielectric separation is mandatory [76].

Below is a comparative analysis table evaluating the different passive protection solutions based on the structural profile geometry.

Table 13 - Performance evaluation of Circular, Ω - Profile, C-Profile, and H-Profile geometries regarding adhesion, durability, and application complexity.

Profile geometry	Adhesion	Adaptability to sharp curvatures	Durability	Cost	Ease of application	Coverage
Circular	Excellent	Very high	Very high	Low	Very simple	Perfect
Ω	Very good	High	High	Medium	Simple	Excellent
C	Poor	Low	Moderate	High	Complex	Difficult
H	Poor	Low	Moderate	Very high	Very complex	Difficult

7.3.2. Active protection with correct galvanization thickness

Parallel to the implementation of dielectric physical barriers that prevent direct contact between the structural steel and the corrosive telluric environment, the foundations of an agrivoltaic plant mandate the mandatory integration of active protection schemes [15]. The absolute reliability of passive barriers can inevitably be compromised by mechanical damage. A single deep scratch, caused by the severe friction against a compact stone in the deep soil horizons during the brutal hydraulic ramming operations, exposes the bare structural steel directly to the aggressive agricultural fertilizers. The engineering mitigation to prevent this localized vulnerability from degenerating into a rapid structural perforation relies on the electrochemical reactivity of sacrificial metals through cathodic protection [72]. This approach is founded on the scientific control of electron flows, dictating that the environmental degradation must discharge entirely onto a consumable metallic mantle rather than onto the static load-bearing core.

The fundamental science of this active protection in solar infrastructure relies almost exclusively on zinc. According to the galvanic series, zinc acts as a massive sacrificial anode when placed in electrical contact with carbon steel. It continuously emits electrons that flood the steel matrix, forcing it into an immune electrochemical potential and artificially suppressing its tendency to oxidize, even if the steel is widely exposed following severe lacerations [72]. However, determining the correct application method, the optimal alloy, and the precise thickness of this coating is the most critical engineering challenge for agricultural applications.

Heavy batch galvanization and advanced zinc alloys

The primary active mitigation strategy involves an overall increase in the applied sacrificial mass. In standard, uncultivated soils with high electrical resistivity, a

standard minimum hot-dip galvanization layer of 70 to 85 μm , regulated by the ISO 1461 standard, can easily survive unharmed for decades [28]. However, the intensive agronomy and widespread fertigation practices found in agrivoltaic parks permanently alter this equilibrium. The bioconversion of nitrogenous fertilizers generates localized excesses of hydrogen ions that violently acidify the interstitial water, while applied sulfates and chlorides react with the active zinc to form highly water-soluble salts. Washed away by continuous irrigation, these soluble salts physically remove the protective metal.

Under these aggressive agricultural conditions, the air-soil transition zone experiences an accelerated depletion of the sacrificial layer, with a uniform corrosion rate that can easily reach 10 μm per year. This rate is almost double the average corrosive behavior expected in standard soils. Consequently, standard galvanization thicknesses cannot possibly compensate for this dissolution over the required thirty-year lifespan of an agrivoltaic project. To overcome this, the vertical pile must be engineered with ultra-heavy batch galvanization, targeting thicknesses between 85 and 120 μm [15].

Alternatively, a far more efficient coating strategy involves shifting towards the use of advanced ternary alloys, specifically zinc-aluminum-magnesium coatings. These specific alloys have demonstrated vastly superior performance in underground environments compared to pure zinc. When exposed to the telluric electrolyte, the magnesium facilitates the rapid precipitation of highly stable, insoluble hydroxides, such as aluminum-modified simonkolleite. This complex dense layer is incredibly resilient to sudden pH drops and to the ammoniacal fluids typical of animal manure. By applying high-thickness zinc-aluminum-magnesium coatings, such as the ZM1000 designation which provides approximately 1000 g/m^2 , the pile gains an unbeatable sacrificial buffer. These heavy monolithic coatings are easily applicable to all profile geometries, including H-profiles, C-profiles, and Ω sections, providing excellent overall structural resilience against installation abrasion.

Localized active protection via zinc-rich paints

When structural constraints, economic limits, or the complex re-entrant geometry of certain profiles disincentivize the use of heavy monolithic galvanization or solid polymeric sleeves, a highly targeted active intervention involves the application of zinc-rich paints. It is crucial to specify that these primers should not be confused with purely hydrophobic barrier paints; they are actual electrochemical prostheses engineered for active cathodic protection [15].

To function effectively, the formulation must contain an extremely high concentration of pure micro-fine zinc dust, strictly exceeding 80 to 85 % by mass in the final dry film. This titanic density is required to satisfy the percolation theory, forcing the individual spheroidal zinc particles to physically collide with each other in an uninterrupted structural tangle within the resin vehicle. This continuous metallic network closes a

circuit of total electrical conductivity with the underlying original galvanization or the bare steel of the pile.

This specific coating solution is optimally applied in a strictly localized manner, concentrating exclusively on the highly vulnerable air-soil transition interface. Engineering best practices suggest applying these zinc-rich primers in a continuous band extending from 20 cm above the ground level down to 40 or 50 cm below the subsoil [15]. By applying an additional layer of approximately 60 μm of zinc-rich paint strictly in this critical splash zone, the designer provides a massive, localized sacrificial reservoir exactly where the differential aeration cell is most destructive.

The application of zinc-rich paints offers a unique dual-action life extension mechanism. When the aggressive telluric electrolyte attacks this painted zone, the galvanic storm preferentially consumes the millions of grains of zinc powder suspended in the resin rather than attacking the structural steel. Subsequently, as the pulverized zinc undergoes oxidation, the resulting zinc oxides and sulfates swell significantly in volume. Confined within the tough grip of the epoxy or silicate binder, these voluminous white reaction products generate a plugging effect. They physically saturate the remaining microscopic pores of the polymeric ring, progressively inhibiting deep gaseous exchange and transforming the active primer into an impenetrable passive armor [15]. This solution is particularly advantageous for C-profiles, where the liquid paint can be sprayed or brushed directly into the difficult re-entrant corners, ensuring active protection even in geometrically complex areas without the bridging issues typical of heat-shrinkable sleeves.

Architectural redesign through split-pile systems

In the context of modern agrivoltaic architecture, the structural design introduces a further economic and logistical complication. To allow the free transit of heavy, energy-intensive rural mechanization, such as tractors and harvesters, beneath the solar panels, the vertical piles must exhibit a high net elevation clearance. This clearance routinely exceeds 2.1 to 3.5 m in height. Adding the necessary anchored depth of 1.5 to 2.5 m for geotechnical stability in agricultural clays, the structural designer must utilize extremely long metallic profiles reaching up to 8 m in total length [15].

Protecting such a massive monolithic pile with exceptionally heavy batch galvanization exceeding 100 μm simply to resist the saturated agricultural soil results in a dramatic economic contradiction. It forces the deposition of 3/5 of that massive and costly zinc mass onto the upper aerial column, where the extreme telluric aggressiveness is completely absent, resulting in a severe waste of valuable material. The aerial fraction of the structure is subjected exclusively to atmospheric corrosivity. While the constant evapotranspiration of the underlying crop leaves and the deposition of chemical aerosols from fertigation preclude the use of the overly cautious

and benign C2 classification, this rural atmosphere should be correctly classified as a C3 medium corrosivity environment [38]. Coastal proximity or specific industrial pollution would elevate this to C4 or C5, but in standard inland agrivoltaics, C3 is the correct normative target. In a C3 atmosphere, a standard continuous hot-dip galvanization layer consumes only 0.7 – 2.1 μm per year.

The definitive engineering proposal to resolve this cost-survival equation is the implementation of a split-pile foundation system, also known as a two-section pile architecture. This approach mechanically decouples the fate of the underground anchorage from the above-ground photovoltaic support structure. The lower root section, destined to suffer the acidic environment of fertigation, high capillary stagnation, and the mechanical impact of ramming, is engineered with ultra-heavy batch galvanization ranging from 85 to 120 μm , or by utilizing heavy-duty zinc-aluminum-magnesium alloys capable of surviving the severe immersion condition.

Conversely, the upper column section, physically disconnected from the soil risk, relies on economical, continuously galvanized steel coils with standard commercial thicknesses. A Z350 designation, providing approximately 25 μm of zinc, or an equivalent lightweight zinc-magnesium layer, is perfectly adequate to guarantee the lifespan required for the C3 atmospheric exposure. Furthermore, utilizing zinc-magnesium alloys for the upper section leverages their self-healing effect, migrating to protect the inevitable cold cuts and bolt holes that abound in the aerial framing these junction point between the two distinct modules is usually bolted via connecting flanges approximately 1 m above the ground, intentionally keeping the connection safely above the splash dirt zone [15].

Comparative analysis of active protection options

The following table provides a synthetic comparative evaluation of the different active protection strategies discussed, summarizing their operational parameters and their specific adaptability to structural profiles.

Table 14 - Comparative analysis of different active protection strategies based on technical performances.

Active protection strategy	Adhesion	Adaptability	Durability	Cost	Simplicity	Coverage	Abrasion resistance
Localized zinc-rich paint	Moderate	High	Moderate	Low	Moderate	High	Low
Zn-Al-Mg alloy pile	Very high	Very high	Very high	Moderate	Very high	Very high	Very high

Heavy buried galvanization	Very high	High	High	Very high	Very high	Very high	High
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7.4. Future outlook and predictive maintenance

As the solar energy sector matures and the integration of photovoltaic technology with agricultural practices becomes structurally and normatively codified, the engineering focus must inevitably shift from mere installation to long-term lifecycle management. This final chapter provides a comprehensive future outlook on the research trajectories regarding corrosion prevention in photovoltaic and agrivoltaic plants. The transition from a reactive maintenance approach to a predictive and preventative paradigm is an absolute necessity to guarantee the financial viability and structural safety of these multi-decade investments.

To fully understand the urgency of this transition, it is essential to contextualize the historical development of the European and Italian solar markets. The first pioneering photovoltaic plants were installed in the early 2000s, but the true explosive growth of the sector occurred around the year 2011, driven by massive public incentive schemes such as the Italian Conto Energia [77]. Today, the vast majority of the infrastructural backbone of this first great solar wave is approaching or exceeding fifteen years of continuous operation. This noticeable aging of the metallic support structures poses a severe engineering challenge. Many of these early utility-scale plants were designed and driven into the ground without extensive preliminary geotechnical corrosion studies, often relying on standard galvanization thicknesses and structural dimensioning that lacked substantial safety coefficients for underground degradation.

Given the particular aggressiveness of certain soils, characterized by low resistivity or high acidity, the degradation rates of these older structures might have already compromised their load-bearing capacity. Consequently, it is now strictly necessary to perform rigorous field verifications on the state of the structural supports of that era. In cases where the underground foundation profiles show critical thinning due to localized pitting or generalized anodic dissolution, it becomes imperative to plan a complete revamping of the plant as soon as possible. Revamping, in this context, implies the total decommissioning and integral replacement of both the photovoltaic modules and the underlying metallic structures.

A more complex decision-making scenario arises when plant operators consider the practice of repowering. Repowering involves replacing the old, degraded photovoltaic modules with modern, high-efficiency panels to maximize the energy yield of the existing land footprint, while maintaining the original support structures to save on capital expenditures. However, applying a purely electrical perspective to repowering

is a dangerous financial oversight. It is absolutely crucial to scientifically verify the residual life of the structural steel before proceeding with the installation of new panels. If a site is repowered without a structural assessment, the operator risks mounting modules guaranteed for 25 to 30 years onto a galvanized structure that might collapse under wind loads within the next five years due to hidden underground corrosion. The subsequent failure would force the operator to incur the massive double cost of dismantling the newly installed panels, extracting the failed piles, driving new foundations, and remounting the panels. Therefore, predicting the residual structural life is the fundamental prerequisite for efficient and economically rational repowering.

To prevent the errors of the past and protect future agrivoltaic investments, the industry must adopt a standardized, tiered approach to soil characterization. It is essential to structure a geochemical analysis plan of simple execution and low cost to obtain a primary perspective of the site before any mechanical design takes place. This initial screening should focus on easily measurable macro-parameters that heavily influence the telluric electrolyte, primarily the hydrogen-ion concentration, the specific electrical resistivity, the gravimetric moisture content and the water table [19]. This basic soil profiling requires minimal financial effort but immediately highlights potential red flags. If this preliminary low-cost analysis reveals critical values, such as a highly acidic environment or an electrical resistivity plummeting below $20 \Omega \cdot \text{m}$, the engineering protocol must mandate a much more profound, detailed, and expensive chemical investigation. This secondary analysis would quantify the presence of specific depolarizing agents like sulfides, chlorides, and agricultural sulfates, allowing for a custom-tailored calculation of the required sacrificial zinc mass. Furthermore, for large-scale utility projects where the initial capital expenditure is massive and the relative cost of geotechnical surveys becomes statistically negligible, a detailed geochemical analysis must be considered a mandatory, non-negotiable step prior to the structural design phase.

The modern agrivoltaic context introduces a fascinating new variable into structural engineering: the biological and agronomic intent of the land. In the future, the specification of the protective coating cannot be a mere mathematical abstraction based solely on raw soil data, it must be intimately coordinated with the specific typology of crop cultivation and the precise fertilization cycles that will be implemented over the next three decades. Different crops dictate vastly different microclimates and chemical inputs. For example, an agrivoltaic structure shading a permanent pasture for sheep grazing will face a relatively stable, low-input soil environment. Conversely, a structure integrated into an intensive horticultural layout, such as tomato or corn cultivation, will be subjected to massive, cyclical injections of nitrogen, phosphorus, and potassium fertilizers, alongside frequent artificial drip irrigation. These soluble salts drastically lower the soil resistivity and accelerate the consumption of amphoteric

zinc coatings [15]. Therefore, the structural engineer and the agronomist must collaborate; the choice between standard hot-dip galvanization, advanced zinc-aluminum-magnesium alloys, or the application of supplemental polyurethane barriers at the air-soil interface must be directly influenced by the agronomic plan.

The most promising frontier for the long-term preservation of agrivoltaic assets lies in the implementation of predictive maintenance powered by continuous environmental monitoring. Current normative frameworks and incentive guidelines for agrivoltaics actively mandate the installation of advanced monitoring systems to verify the impact of the solar installation on crop yield, water savings, and microclimate variations [4]. This requirement results in the deployment of a dense network of field instrumentation, including weather stations, ambient and soil temperature sensors, deep soil moisture probes, and continuous pH meters.

From a corrosion engineering perspective, this agronomic sensor network represents an invaluable, already-funded digital infrastructure that can be seamlessly repurposed for structural monitoring. The data streams continuously generated by these instruments offer a real-time window into the electrochemical aggressiveness of the telluric environment. It is highly advantageous to utilize this data to feed dynamic predictive models capable of estimating the ongoing wear state of the underground structures. The rate of metallic degradation is not linear; it accelerates during periods of high soil saturation and temperature, and spikes immediately following the localized application of liquid fertilizers.

By capturing the precise variations in soil moisture, temperature, and pH, engineers can calculate the actual time of wetness of the buried steel and the real-time conductivity of the electrolyte. In particular, the continuous analysis of the pH, the moisture levels, and the concentration of dissolved fertilizers, specifically expressed as nitrogen, phosphorus, and potassium macro-elements, provides data of immense value. While collected primarily for agronomic purposes to optimize fertigation, when these specific chemical parameters are integrated with the electrical conductivity readings, they permit a more than satisfactory control of the environmental boundary conditions driving the corrosion cell.

This continuous digital monitoring must be coupled with a scheduled protocol of physical field inspections. It is highly recommended to perform targeted inspections at least every five years. These inspections should involve the localized excavation of the soil around a statistically significant sample of foundation piles to expose the critical air-soil transition zone. Utilizing non-destructive testing equipment, such as ultrasonic thickness gauges, technicians can measure the exact residual thickness of the protective zinc layer.

The physical measurements obtained during these 5-year inspection cycles serve to calibrate and update the predictive mathematical models fed by the continuous

agronomic sensors. If the sensors detect a prolonged period of high soil acidity and moisture due to a change in agricultural practices, the predictive model will automatically steepen the forecasted corrosion curve, alerting the asset manager. The subsequent physical inspection will then verify this accelerated degradation.

Ultimately, this synergy between continuous agro-environmental data and periodic physical validation allows plant owners to move beyond static, theoretical design lifespans. It creates a dynamic reliability index for the power plant [18]. By accurately mapping the remaining structural thickness against the known mechanical loads, operators can perform predictive verifications. This methodology grants the ability to anticipate the necessity of future revamping interventions long before catastrophic wind-induced failures occur. More importantly, it empowers stakeholders to evaluate the economic feasibility of repowering with absolute confidence, ensuring that the heavy investments in next-generation photovoltaic modules are securely anchored to support structures that possess a scientifically verified and sufficient residual life.

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