COATINGS, WELDED JOINTS AND MICROBIAL COLONIZATION IN HOOP AND CONVENTIONAL SWINE HOUSING SYSTEMS

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Abstract

This study evaluates the long-term performance of protective coatings and welded joints in semicylindrical hoop and conventional swine housing structures built between 2008 and 2011 and operated for approximately 15 years, using dry film thickness measurements (ISO 2808) and coating degradation ratings (ISO 4628). Hoop buildings exhibited better preservation of protective coatings and welded joints than conventional facilities, which, characterized by higher humidity and ammonia concentrations, showed more extensive deterioration of protective layers and a greater occurrence of localized corrosion, particularly around structural assembly joints and welded areas.

A complementary microbiological investigation revealed that corroded surfaces retained higher microbial colonization than intact coated areas, with bacteria and fungi colonizing rough and porous rust layers. Housing design and microclimate therefore significantly affect coating service life and the extent of corrosion-associated microbial reservoirs on metal surfaces.

Key words: *hoop structures, swine housing, welded joints, corrosion, microbial colonization*

INTRODUCTION

Steel frames are the most widely used structures in industrial pig production. Inside livestock buildings they are exposed to one of the most aggressive indoor atmospheres encountered in agricultural constructions: high relative humidity, frequent condensation and air loaded with ammonia, hydrogen sulphide, carbon dioxide, organic acids and dust originating from manure and feed. According to ISO 12944-2, such interiors correspond to the high corrosivity categories C4–C5 [1]. The long-term durability of the surface coating system is therefore a key factor for the maintenance needs and the service life of these structures.

Two structural concepts are common in pig housing (Fig. 1). Conventional buildings are steel portal frames with an insulated roof, fully enclosed ends and curtain-ventilated longitudinal walls, often including a heated service / hospial area. Comparative to conventional structures, hoop structures consist of semicylindrical steel arches covered with a fabric membrane - they are naturally ventilated over their entire length and have no insulated roof cavity [2]. The two concepts create very different microclimates around the steel members, but their effect on the long-term condition of coatings and welded joints has rarely been documented in the field.

Metal surfaces within swine facilities can act as important microbial reservoirs, particularly when protective coatings are degraded and corrosion products are present. Corroded steel surfaces exhibit

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increased roughness, porosity and moisture retention, creating protected niches that facilitate the attachment, survival and persistence of bacteria and fungi despite routine sanitation procedures. The efficacy of cleaning and disinfection is generally reduced on rough and porous surfaces because organic matter, biofilms and microorganisms can remain embedded within surface irregularities that are inaccessible to detergents and disinfectants. From a biosecurity perspective, such surfaces may contribute to the environmental persistence of animal pathogens and increase the risk of pathogen transmission within livestock facilities. In addition, microbial communities associated with corrosion products may actively participate in microbiologically influenced corrosion (MIC), accelerating metal deterioration through the activity of sulfate-reducing, sulfur-oxidizing and iron-oxidizing microorganisms. Consequently, maintaining intact protective coatings and minimizing corrosion are important not only for structural durability but also for hygiene and biosecurity management in swine production systems [3].

The aim of this study was to compare the condition of protective coatings and welded joints in hoop and conventional swine buildings after approximately 15 years of operation, using dry film thickness measurements (ISO 2808) [4] and standardized degradation ratings (ISO 4628) [5] - to relate the observed damage to building design and microclimate, and, in a complementary microbiological study, to compare the microbial colonization of corroded and intact coated surfaces



Fig. 1 General view of the investigated housing systems:(a) conventional steel portal-frame building with enclosed gables and longitudinal curtain walls; (b) hoop structure with semicylindrical steel arches and fabric cover

MATERIAL AND METHOD

Investigated structures

The study covered conventional and hoop swine housing units located in the western part of Romania, built between 2008 and 2011 and operated continuously for approximately 15 years.

The conventional buildings are steel frames with hot-rolled H-section columns and rafters. The roof is supported by cold-formed Z-profiles fixed through welded U-shaped plates. The roof is a constructed built-up assembly: an inner steel liner is fixed to the underside of the rafters, the cavity between the liner and the outer trapezoidal steel sheet is filled with mineral wool, and the rafters, cleats and purlins are embedded in this insulation layer. The ends are fully enclosed from floor to ridge, while the longitudinal walls consist of a low plinth with adjustable curtains above it.

The hoop buildings consist of semicircular painted steel tubular arches covered with a PVC fabric membrane anchored on sidewalls. Natural ventilation acts over the entire structure, and there is no enclosed roof cavity or insulation layer.

Zoning of the conventional buildings

At the entrance end, each conventional building contains a service and hospital area that houses the automation and control equipment and is actively heated. Because this end is enclosed from floor to ridge, it is not ventilated by the longitudinal curtain

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system, and its air exchange is substantially lower than along the rest of the building.

For assessment, each building was divided into Zone A (heated service and hospital end), Zone B (transition) and Zone C (production section with longitudinal curtain ventilation) (Fig. 2).

Two additional levels were assessed separately: the roof level (purlin-to-rafter connections, cleats and welded roof joints) and the lower column sections adjacent to the plinth wall. External column faces were also assessed separately.

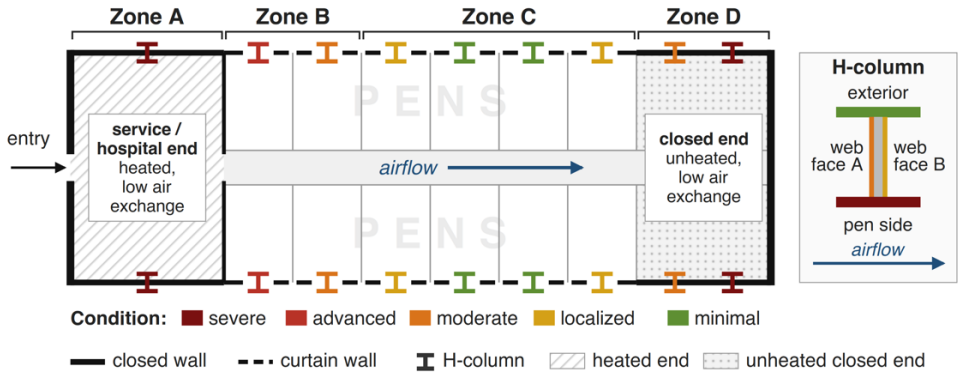


Fig. 2 Plan view of a conventional building: heated service/hospital zone (A), transition zone (B) and curtain-ventilated pen area (C), with enclosed gable walls, curtain walls and longitudinal airflow; colours indicate the observed column condition. Left figure - plan view of H-column

Coating systems and exposure

The conventional structures were protected by an epoxy primer + polyurethane topcoat with a nominal dry film thickness (NDFT) of 200-300 µm, consistent with the 180–250 µm range typically specified for high-durability systems in C4 environments [6]. The hoop arches were protected by the same painting system configuration. The interiors of livestock buildings correspond to the interior descriptions of categories C4–C5 in ISO 12944-2, which refer to high humidity, frequent condensation and significant pollution [2]; the heated, poorly ventilated service zone lies at the upper end of this range.

Dry film thickness measurements

DFT was measured non-destructively according to ISO 2808 [4], using a VIAGTOOL VC-200 magnetic induction gauge calibrated on certified foils before each measurement session (Fig. 3). Sampling and acceptance criteria followed ISO 19840 [8]: the arithmetic mean must be equal to or greater than the NDFT, and no individual reading may fall below 80% of the NDFT. Measurements were taken only where an adherent coating remained; areas with complete coating loss were recorded as "not measurable" and assessed visually.



Fig. 3 DFT measurement according to ISO 2808 - magnetic induction gauge applied on a column

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On each H-section column, readings were taken on four faces: the inner flange facing the pens, the two web-side faces (oriented towards opposite ends of the building) and the outer flange facing the exterior. Columns were sampled at three heights: low (plinth level), mid (curtain level) and high (roof connections).

Coating degradation assessment

Coating condition was rated according to the ISO 4628 series [5]: rusting (Ri 0-5, ISO 4628-3), blistering (ISO 4628-2), cracking (ISO 4628-4) and flaking (ISO 4628-5). For the degree of rusting, Ri 0 corresponds to 0% rusted area, Ri 3 to about 1%, Ri 4 to about 8% and Ri 5 to about 40-50%. Where the coating was completely lost, the condition of the steel substrate was described using the rust grading of ISO 8501-1 [9].

Welded joints and bolted assembly connections were examined visually for coating loss at weld toes and edges, rust bleeding, crevice corrosion and exfoliating (layered) rust. The condition of the weld preparation was interpreted with reference to ISO 8501-3 [10], and design-related corrosion traps with reference to ISO 12944-3 [11].

Microbiological sampling. Microbiological samples were collected from paired steel surfaces consisting of visibly corroded areas and adjacent intact coated surfaces located at the same measurement points used for DFT assessment (Zones A, B and C, roof-level structural elements and lower columns, including inner flange faces, web surfaces and external faces). Sampling was performed using sterile sponge-swabs pre-moistened with neutralizing buffer, following the principles described in ISO 18593:2018 for surface sampling in the food and animal production environment [12]. A standardized sampling area of 100 cm² (10 × 10 cm) was delineated using sterile templates, and each surface was swabbed using horizontal, vertical and diagonal strokes to maximize microbial recovery. Samples were collected 24 h after routine cleaning and disinfection procedures to evaluate residual microbial contamination. For each building type (conventional and hoop structure), five replicate samples were obtained from each structural zone and surface condition (corroded versus intact coated), resulting in a total of 60 samples. Following collection, samples were placed in sterile transport containers, maintained at 4°C during transport, and processed within 24 h of sampling to minimize changes in microbial viability.

Statistical analysis

DFT readings were summarised per zone and column face as range, arithmetic mean and standard deviation, and compared with the NDFT and the 80% NDFT limit of ISO 19840 [8]. The frequencies of microbiologically positive samples were compared between conventional and hoop buildings using the chi-square test, whereas microbial colonization were compared by two-way ANOVA, considering building type and surface condition (corroded vs. intact coated) as fixed factors ($p < 0.05$).

RESULTS

Conventional buildings: longitudinal gradient

Coating degradation followed a clear gradient along the length of the conventional buildings (Table 1, Fig. 4). In Zone A no residual coating was present on the columns; the steel was covered with thick, laminar rust that detached spontaneously from the column surfaces, so DFT could not be measured. The condition corresponded to Ri 5 and to ISO 8501-1 rust grade D. Moving away from the service zone, corrosion on the side columns decreased progressively, and areas of intact coating appeared among the corroded areas.

Where coating remained (Zones B and C), measured DFT ranged from 58 to 252 µm (mean 138 µm, SD 72 µm, n = 8). 75%

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of readings fell below the NDFT (200 µm) and 75% below 80% of the NDFT, indicating local thinning through erosion and corrosion undercutting. Ri values in Zones B and C ranged from Ri 2 to Ri 4. Towards the opposite direction, unheated closed end (Zone D), corrosion increased again (Ri 5), with residual coating of 81–111 µm (mean 94 µm, n = 4).

Table 1 DFT and ISO 4628 ratings by zone (conventional buildings)

Zone	**DFT range** *(µm)*	**Mean ± SD** *(µm)*	**Ri** *(ISO 4628-3)*	**Flaking** *(ISO 4628-5)*	**Observations**
A – heated service end	n.m.	–	Ri 5	complete	Exfoliating rust, no residual coating
B – transition	58–117	88 ± 32	Ri 4	4	Thin residual coating, extensive rusting
C – ventilated section	123–252	189 ± 66	Ri 2	2	Localized corrosion, mainly on inner flange
D – unheated closed end	81–111	94 ± 15	Ri 5	5	Severe corrosion, thin residual coating
Roof connections	n.m.	–	Ri 5	complete	Advanced corrosion at Z-purlins, U-cleats and welds
Lower columns	93–160	116 ± 38	Ri 2	2	Coating largely retained, thinned
External faces	74–200	126 ± 66	2	1	Minimal corrosion

Note: *n.m. - not measurable (complete coating loss); DFT - dry film thickness; SD - standard deviation; NDFT - nominal dry film thickness (200 µm). n = 3-4 readings per zone.*



Fig. 4 Longitudinal gradient of coating degradation: (a) heated service zone, Ri 5, complete coating loss; (b) transition zone; (c) curtain-ventilated section with residual coating (DFT 100–250 µm)

Face-dependent degradation phenomena observed on H-section columns

Within a single column, degradation depended strongly on orientation (Fig. 2, Fig. 5). The inner flange facing the pens was consistently the most corroded surface. The two web-side faces were asymmetric: one side was more corroded than the other, the more corroded side being downstream relative to the dominant airflow direction. The external faces showed only minimal corrosion.

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Fig. 5 Face-dependent degradation of an H-section column: (a) pen side & downwind side; (b) pen side & upwind (under longitudinal airflow);

Vertical distribution, structural connections and welded joints

Corrosion severity varied significantly with height (Fig. 6). The lower column sections adjacent to the plinth wall retained their coating in very good condition. At roof level, corrosion was comparable to that of Zone A. The Z-profiles and the U-plates connecting them to the rafters showed advanced corrosion, concentrated at the purlin–rafter interfaces and in the welded roof joints (Fig. 7). At these locations the coating was lost first at weld toes, plate edges and overlapping contact surfaces, and laminar rust then developed from these points.

Hoop buildings

Hoop structures were assessed visually according to ISO 4628. The protective coating was preserved over most of the structure, with only minimal, isolated corrosion (Ri1 1), mainly at anchorages and fastener points (Fig. 8). No zone of concentrated deterioration comparable to the service zone or the roof connections of the conventional buildings was identified. Welded and bolted joints of the arches showed only superficial rust staining.

Culture-based analyses indicated the presence of bacterial groups morphologically consistent with *Bacillus spp., Staphylococcus spp., Pseudomonas spp.* and *Enterobacteriaceae*, together with fungal isolates consistent with *Aspergillus spp., Penicillium spp.* and *Cladosporium spp*. Compared with intact coated surfaces, corroded areas showed higher microbial abundance and diversity, likely due to increased surface roughness, porosity, and moisture retention that favor biofilm formation.



Fig. 6 Vertical distribution of corrosion on the same column: (a) lower section adjacent to the plinth wall; (b) upper section at roof level; (c) roof U-plates

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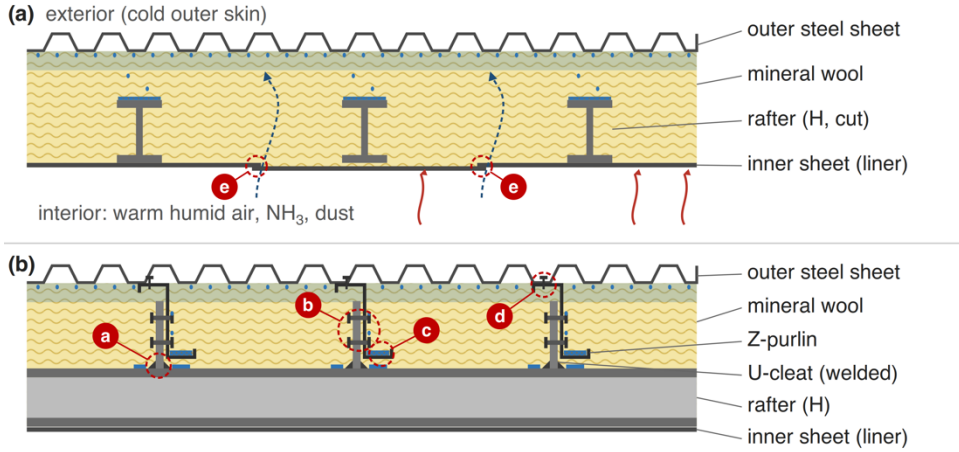


Fig. 7 Roof assembly of the conventional buildings. (a) Longitudinal section: warm, humid air containing ammonia enters the insulated cavity through liner joints and condenses on the cold side (blue: condensate and wetted insulation). (b) Purlin-rafter connection with corrosion-critical locations: (a) fillet weld; (b) bolted assembly; (c) upturned lip of the purlin bottom flange retaining condensation and dust; (d) purlin-outer sheet thermal bridge; (e) liner laps and penetrations



Fig. 8 Hoop structure after about 15 years of service: (a) arch with preserved protective coating; (b) arch joint showing minimal corrosion (Ri 1)

The presence of these microorganisms highlights the dual role of corroded surfaces as potential biosecurity hazards and contributors to microbiologically influenced corrosion (MIC) in swine production facilities.

Microbial contamination was significantly influenced by both surface condition and building type (Table 2). Corroded steel surfaces consistently harboured higher microbial colonization than adjacent intact coated surfaces ($p < 0.001$). The highest microbial counts were recorded in the heated service area (Zone A) and at roof connections of conventional buildings, where severe coating degradation (Ri 5) and extensive rust formation provided favourable conditions for microbial attachment and persistence. Microbial colonization represent total culturable aerobic microorganisms expressed as $\log_{10}$ CFU/cm². Mean loads on corroded surfaces in these locations exceeded those measured on intact coated surfaces by approximately 1.0-1.5 log CFU/cm². In contrast, the ventilated production section (Zone C) showed significantly lower contamination levels ($p < 0.05$), while lower column sections and external faces exhibited the lowest microbial burdens. Overall, conventional buildings showed higher microbial colonization than hoop structures ($p < 0.01$), likely reflecting poorer ventilation and greater corrosion severity and the greater extent of coating deterioration. In hoop buildings, where corrosion was limited to isolated areas classified as Ri 0-1, microbial counts remained relatively low and differences between corroded and intact surfaces were less pronounced.

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Table 2 Microbial colonization by zone and surface condition

Zone	Corroded surfaces (log CFU/cm²)	Intact coated surfaces (log CFU/cm²)	Diffe-rence	P - value	Observations
A – heated service end	5.8 ± 0.4	4.3 ± 0.3	+1.5	<0.001	Highest contamination; extensive rust and retained deposits
B – transition	5.1 ± 0.5	4.0 ± 0.4	+1.1	<0.01	Moderate contamination associated with partial coating loss
C – ventilated section	4.5 ± 0.4	3.7 ± 0.3	+0.8	<0.05	Lower counts due to improved ventilation
D – unheated closed end	5.5 ± 0.4	4.2 ± 0.4	+1.3	<0.01	Elevated contamination on heavily corroded surfaces
Roof connections	6.0 ± 0.5	4.4 ± 0.4	+1.6	<0.001	Highest microbial colonization; corrosion traps and condensation
Lower columns	4.1 ± 0.3	3.5 ± 0.3	+0.6	<0.05	Limited colonization; coating largely preserved
Conventional building (overall)	5.4 ± 0.5	4.1 ± 0.4	+1.3	<0.001	Significantly higher microbial burden associated with extensive corrosion (Ri 4-5)
Hoop building (overall)	4.2 ± 0.4	3.8 ± 0.3	+0.4	<0.05	Lower contamination levels; only isolated corrosion site

Note: Values represent total culturable microbial counts obtained on Plate Count Agar after incubation at for 48 h. Values expressed as mean ± SD $\log_{10}$ CFU/cm².

DISCUSSIONS

Microclimate as the governing factor

The distribution of damage indicates that local microclimate, rather than coating specification, governs coating service life in these buildings. Both building types were protected by systems of comparable nominal performance, yet their condition after about 15 years differed sharply; within the conventional buildings, damage ranged from complete coating loss to a near-intact coating over only a few tens of metres.

The most severe degradation occurred in the heated, enclosed service zone. There, higher temperature accelerates corrosion kinetics, while low air exchange keeps relative humidity high. Moist air meeting steel surfaces that are colder than the surrounding air (thermal bridges) produces condensation. Together, these factors prolong the time of wetness, the primary driver of atmospheric corrosion [13].

Role of ammonia and livestock-derived contaminants

Gaseous ammonia alone is only mildly aggressive toward carbon steel. In livestock buildings, however, it dissolves in surface condensate and, together with CO_2, H_2S, organic acids and chlorides from manure and feed dust, forms hygroscopic ammonium salts and deposits [14].

These deposits lower the relative humidity at which surface moisture films form, so the steel stays wet for longer and its surface electrolyte is more conductive.

This mechanism is consistent with two observations. First, the inner flanges facing the pens, directly exposed to animal-level air and dust, were the most corroded column faces.

Second, one web-side face was more corroded than the other: under longitudinal airflow, the leeward face lies in a zone of reduced air velocity, where contaminants and moisture accumulate and drying is slower, while the windward face is swept and dried more effectively.

Roof assembly and welded connections

In the conventional buildings, the rafters, U-plates and Z-profiles are enclosed within the insulated cavity between the inner liner and the outer sheet (Fig. 7). Warm, humid air loaded with ammonia and other contaminants can enter this cavity through liner laps and fastener penetrations, diffuse through the mineral wool and

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condense on the cold side of the assembly, beneath the outer sheet and on the purlin flanges in contact with it [15].

The condensation drips onto the lower commponents and is retained in the wetted insulation, in the area formed by the upturned lip of the purlin bottom flange and on the rafter flanges around the welded cleats. Being closed, these locations cannot dry by ventilation and are not accessible for inspection or maintenance.

At the same locations, the coating is inherently weaker: coatings thin and do not adhere properly at sharp edges and weld toes; weld spatter, porosity and residual slag remain where weld preparation did not reach proper results, such as ISO 8501-3 grade P3 [10]; and bolted overlaps form crevices that cannot be coated to full thickness - corrosion traps in the sense of ISO 12944-3 [11]. This explains why damage at roof level resembled that of the service zone, even though the two areas are far apart. The good condition of the lower column sections, shielded by the plinth wall and located below the zone where warm, moist air accumulates, is consistent with this interpretation.

Hoop versus conventional design

The better preservation observed in hoop buildings can be attributed to ventilation acting over the entire structure, the absence of enclosed heated end zones and of an insulated roof cavity, and a simpler geometry – an arch with few crevice-forming connections.

Altogether, these features reduce the time of wetness over the whole structure. For livestock buildings, corrosion design should therefore target the zones of low air exchange and the structural connections, not only the coating specification: a higher-durability system (C5, durability "H" or "VH" according to ISO 12944-5 [6]) in enclosed or heated zones and at roof connections, stripe coats on welds and edges, and connection details that do not form crevices.

Although hoop barns are often associated with improved natural ventilation and lower concentrations of noxious gases compared with conventional swine facilities, the greater exposure of structural components to fluctuating temperature, humidity and condensation may enhance the degradation of protective coatings. Consequently, corroded metal surfaces may become important microbial reservoirs, reducing the effectiveness of cleaning and disinfection procedures and creating favorable conditions for microbiologically influenced corrosion. In contrast, conventional enclosed facilities provide better environmental control but may maintain elevated concentrations of ammonia and moisture that also contribute to metallic corrosion. Therefore, corrosion-related biosecurity risks should be considered in both housing systems, albeit through different environmental mechanisms [3].

Integrated implications: coating maintenance as a biosecurity measure

The areas exhibiting the most severe coating degradation, particularly the heated service end and roof connections, also showed the highest microbial colonization, demonstrating that corrosion and coating failure create favorable conditions for microbial persistence. Therefore, maintaining protective coatings in livestock buildings should be regarded not only as a strategy for preserving structural integrity, but also as an essential component of hygiene management and biosecurity.

Limitations

Microclimate parameters (relative humidity, NH_3, temperature) were not monitored, and detailed maintenance history / logs of the buildings were not available. Microbiological findings should be interpreted with caution, as sampling was performed at a single time point and relied primarily on culture-dependent methods, which may underestimate the diversity and abundance of non-culturable micro-

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organisms and fail to capture temporal variations in microbial colonization.

CONCLUSIONS

After approximately 15 years of operation, protective coatings and welded joints were better preserved in hoop buildings than in conventional buildings, even though both were protected by coating systems of comparable nominal performance.

In conventional buildings, coating damage followed the microclimate: complete coating loss in the heated, enclosed service zone, a gradual improvement along the curtain-ventilated section (residual DFT 100–250 µm), and near-intact coatings on lower column sections and external faces.

The most corrosion-prone details were the roof connections - purlin–rafter cleats, welded joints and bolted overlaps embedded in the insulated roof cavity - where concealed condensation, crevices and thin coatings at weld toes combine.

Corrosion protection of livestock buildings should address ventilation and structural detailing together with the coating specification, with higher-durability systems and stripe coats in enclosed zones and at connections.

Corroded surfaces showed consistently higher microbial colonization than intact coated surfaces, indicating that corrosion promotes microbial persistence through increased roughness and moisture retention.

Conversely, hoop structures generally exhibited lower contamination levels than conventional facilities, likely due to improved natural ventilation and reduced moisture accumulation. These findings support coating maintenance and adequate ventilation as complementary strategies for enhancing both structural durability and biosecurity in swine housing systems.

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