Pit Ventilation Systems in Swine Facilities:

Design, Performance, and Management Considerations for Deep-Pit Production Systems

A Comprehensive Review of Pit-Source Ventilation for Air Quality Management, Worker Safety, and Emission Control in Commercial Swine Production

PIGTEK®

ABSTRACT

Pit ventilation systems represent a targeted approach to air quality management in swine facilities with deep-pit manure storage, exhausting contaminated air directly from the manure pit before gases enter the animal living space. This review synthesizes field studies, computational modeling, and operational research conducted over four decades to evaluate the efficacy, limitations, and practical implementation of pit-source ventilation in commercial swine production. Evidence from controlled field trials demonstrates that properly designed pit ventilation systems capture 70–81% of ammonia and hydrogen sulfide emissions at the source, despite representing only 25–40% of total building airflow. This disproportionate capture efficiency creates opportunities for targeted emission treatment and substantially reduces worker exposure to hazardous gases, particularly during manure agitation when lethal hydrogen sulfide concentrations can develop within minutes. However, pit ventilation systems impose capital cost premiums of 10–20%, increase heating costs by 15–30% in cold climates, and require careful design to prevent freezing and maintain proper pressure relationships. Recent advances in variable-speed drive technology and machine-learning control algorithms show promise for optimizing energy efficiency, though field validation at commercial scale remains limited. This review identifies critical research gaps including the absence of quantified energy savings data, limited cold-climate operational protocols, and lack of long-term economic analyses. Producers considering pit ventilation must weigh substantial air quality and safety benefits against increased costs and operational complexity, with greatest applicability in new construction, moderate climates, and facilities facing regulatory or community pressure for emission control.

KEYWORDS

pit ventilation, swine facilities, air quality, hydrogen sulfide, ammonia, worker safety, variable-speed drives, deep-pit manure management

TABLE OF CONTENTS

1. Introduction 3

2. Background and Theoretical Foundations 4

3. Pit Ventilation Systems: Design and Operating Principles 6

4. Air Quality and Gas Management 8

5. Worker Safety 10

6. Animal Welfare and Production Performance 12

7. Economic and Operational Considerations 13

8. Design and Management Recommendations 15

9. Research Gaps and Future Directions 18

10. Conclusion 20

Key Performance Statistics 22

Table 1. Key Field Studies of Pit Ventilation Performance

Table 2. Research Gaps and Implications for Producers

Table 3. Benefits and Drawbacks of Pit Ventilation Systems

References 26

1. INTRODUCTION

Modern intensive swine production in North America relies predominantly on deep-pit manure storage systems beneath slatted floors in finishing, gestation, and farrowing facilities. This design simplifies manure handling by allowing waste to accumulate in below-floor pits for weeks or months before pump-out, eliminating the need for daily scraping or flushing. However, the continuous presence of decomposing manure creates a persistent source of ammonia, hydrogen sulfide, odorous volatile organic compounds, and particulate matter that migrate upward through floor slats into the animal living space [1], [34]. Traditional mechanical ventilation systems address this challenge by exhausting contaminated air from the barn using wall-mounted or ceiling fans, but this reactive approach allows gases to pass through occupied zones before removal, resulting in chronic exposure for animals and workers and limiting opportunities for targeted emission control.

Pit ventilation systems, commonly termed “pit fans” in industry practice, represent a fundamentally different strategy. By installing dedicated exhaust fans that draw air directly from the manure pit space, these systems create negative pressure beneath the slatted floor, capturing gases at their source before they enter the barn environment [4], [34]. This source-capture approach has been investigated since the 1970s, with early model studies demonstrating the theoretical advantages of pit-level exhaust [28]. However, widespread commercial adoption has been constrained by concerns about capital costs, energy consumption, cold-weather freezing risks, and uncertainty about the magnitude of benefits under field conditions.

The past two decades have witnessed renewed interest in pit ventilation driven by multiple converging factors. Regulatory pressure to reduce ammonia and odor emissions has intensified in major swine-producing regions, with some jurisdictions requiring emission control technologies for new or expanded facilities [4], [10]. Growing awareness of occupational health risks in confined animal feeding operations has highlighted the need for improved worker protection, particularly following fatal hydrogen sulfide exposure incidents during manure agitation [2], [45], [54]. Advances in computational fluid dynamics modeling have enabled more sophisticated system design, while variable-speed drive technology and emerging machine-learning control algorithms offer potential pathways to improved energy efficiency [12], [17].

This review synthesizes the current evidence base on pit ventilation systems in swine facilities, drawing on field measurements from commercial operations, controlled experimental studies, computational modeling, and operational research. The objectives are to evaluate the documented benefits and limitations of pit ventilation, provide evidence-based design and management guidance, identify critical knowledge gaps, and offer balanced recommendations for producers considering implementation. The scope encompasses deep-pit finishing, gestation, and farrowing facilities, with primary focus on North American production systems, though relevant European research is included where applicable.

INTRODUCTION

The prevalence of deep-pit systems in modern swine production makes this topic particularly relevant. Survey data indicate that deep-pit manure storage is the dominant system in Midwestern finishing operations, with typical pit depths of 6–8 feet and storage capacity for 6–12 months of manure accumulation [22]. These facilities house the majority of market hogs in major producing states, representing a substantial population of workers and animals potentially affected by air quality management decisions. Understanding the performance characteristics, design requirements, and practical limitations of pit ventilation systems is therefore essential for informed decision-making by producers, designers, and regulatory authorities.

2. BACKGROUND & THEORETICAL FOUNDATIONS

The rationale for pit ventilation emerges from fundamental principles of contaminant transport and the spatial distribution of emission sources in deep-pit swine facilities. Ammonia and hydrogen sulfide are generated primarily through microbial decomposition of nitrogenous and sulfur-containing compounds in stored manure. In deep-pit systems, the manure surface beneath the slatted floor represents the dominant emission source, with fresh excreta on the barn floor contributing a smaller fraction of total emissions [34], [37]. Gases released from the pit surface must diffuse upward through the slats and mix with barn air before reaching wall-mounted exhaust fans in conventional ventilation systems. This transport pathway results in elevated contaminant concentrations in the lower regions of the barn, where animals spend most of their time, and creates spatial heterogeneity in air quality that varies with ventilation rate, temperature, and barn geometry [7], [20], [36].

Computational fluid dynamics modeling has provided detailed insights into airflow patterns and contaminant transport in swine facilities. Three-dimensional simulations of deep-pit finishing barns reveal that conventional wall-fan ventilation creates complex circulation patterns with zones of poor air exchange near the pit surface and in corners distant from exhaust fans [16], [25], [37]. These “dead zones” can accumulate elevated gas concentrations even when overall ventilation rates meet design specifications. The three-zone conceptual model developed by Janni and colleagues describes the pit environment as consisting of a lower zone near the manure surface with high contaminant concentrations, a middle zone within the pit airspace where mixing occurs, and an upper zone immediately beneath the slats where gases enter the barn [37], [56]. This stratification has important implications for ventilation system design, as effective gas removal requires adequate airflow through all three zones.

Pit ventilation alters these transport dynamics by creating a pressure gradient that reverses the normal direction of airflow at the pit-barn interface. When pit fans generate negative pressure in the pit space relative to the barn, air is drawn downward through the floor slats rather than allowing gases to rise upward [4], [27]. This pressure-driven flow intercepts contaminants at their source, preventing their entry into the animal zone. The magnitude of pressure differential required

to prevent updrafting depends on pit ventilation rate, barn ventilation rate, and the resistance to airflow through the slatted floor. Experimental chamber studies have quantified these relationships, demonstrating that pit ventilation rates below a critical threshold fail to maintain negative pressure throughout the pit, allowing localized updrafting in regions distant from exhaust points [27].

The concept of emission partitioning provides a framework for understanding pit ventilation effectiveness. In facilities with both pit and wall exhaust, total emissions can be partitioned into pit-source and barn-source components based on measurements at each exhaust stream [34], [41]. Field studies have consistently demonstrated that pit-source emissions dominate in deep-pit facilities, accounting for 70–80% of total ammonia and hydrogen sulfide release even though pit ventilation typically represents only 25–40% of total airflow [1], [34]. This disproportionate emission capture reflects the spatial concentration of sources near the pit surface and the effectiveness of source-capture ventilation in intercepting gases before dilution in the barn volume.

The theoretical advantages of pit ventilation extend beyond simple source capture to include opportunities for targeted emission treatment. Because pit exhaust contains high concentrations of contaminants in a relatively small airflow stream, it is much more amenable to treatment using biofilters, acid scrubbers, or other control technologies than the large volumes of dilute exhaust from wall fans [4], [10], [47]. The economic feasibility of emission treatment depends critically on the concentration-to-volume ratio, making pit ventilation an enabling technology for facilities required to implement emission controls. Danish and Dutch experience with mandatory emission reduction has demonstrated the practical viability of pit ventilation combined with biofilter treatment, though the regulatory and economic context differs substantially from North American conditions [10], [47].

Pressure relationships within the facility represent a critical design consideration. Proper operation requires a pressure cascade in which outdoor air is at the highest pressure, the barn interior is at intermediate negative pressure relative to outdoors, and the pit is at the lowest pressure [4], [27]. This hierarchy ensures that air flows in the intended direction through inlets, across the animal zone, downward through slats, and out through pit exhaust. If pit ventilation is excessive relative to wall ventilation, the barn can become positively pressurized, causing uncontrolled air leakage through cracks and compromising inlet air distribution. Conversely, insufficient pit ventilation fails to maintain negative pressure in the pit, allowing updrafting of gases. Achieving and maintaining proper pressure relationships across varying seasonal ventilation rates requires careful system design and, ideally, coordinated control of pit and wall fans [3], [11].

3. PIT VENTILATION SYSTEMS: DESIGN & OPERATING PRINCIPLES

Pit ventilation systems consist of dedicated exhaust fans that draw air from the manure pit space, creating negative pressure that captures gases at their source before they enter the barn environment. The fundamental design challenge is to provide adequate airflow to maintain negative pressure throughout the pit while integrating effectively with the barn's overall ventilation system across all seasonal operating conditions. System configurations vary in fan placement, exhaust point distribution, inlet design, and control strategy, with performance depending critically on proper sizing and integration.

The most common configuration in North American swine facilities employs wall-mounted pit fans with horizontal ductwork extending into the pit space to create distributed exhaust points [1], [34]. Fans are typically located on the building sidewall or end wall, with ducts running longitudinally through the pit to collect air from multiple locations. This distributed approach provides more uniform gas removal than single-point exhaust, particularly in longer buildings where a single exhaust point at one end would create uneven pressure distribution and allow updrafting in distant regions [19], [27]. Computational fluid dynamics simulations have demonstrated that exhaust point spacing significantly affects system performance, with recommendations for multiple collection points in buildings exceeding 150 feet in length [16], [25].

Alternative configurations include end-wall exhaust systems where the entire pit serves as a plenum with fans located at one or both building ends, and zone-based systems that divide the pit into independently controlled sections [11], [13], [49]. End-wall systems offer simplicity and reduced ductwork costs but may provide less uniform gas removal in long buildings. Zone-based systems enable independent control of pit ventilation in different barn sections, potentially improving energy efficiency by matching ventilation to local needs, but add complexity and cost [11], [13]. European facilities have explored full pit ventilation systems where all or nearly all building exhaust passes through the pit, but this approach is less common in North America where partial pit ventilation (20–40% of total airflow) predominates [4], [10].

Fan sizing represents a critical design decision with direct implications for system performance and operating costs. Field studies of commercial finishing facilities have documented pit ventilation rates ranging from 13 to 43 cubic feet per minute per pig, with most systems operating in the 20–35 cfm/pig range [1], [34]. The landmark partitioning study by Jacobson and colleagues compared two rooms in a commercial finishing barn, one operating at 27 cfm/pig continuously and another at 27 cfm/pig at night and 43 cfm/pig during the day [34]. Both systems achieved similar emission capture efficiency (70–75% of ammonia, 76–81% of hydrogen sulfide), suggesting diminishing returns above approximately 25–30 cfm/pig. Computational modeling supports this finding, indicating that a minimum threshold ventilation rate is required to prevent updrafting, but rates substantially above this threshold provide limited additional benefit while increasing energy consumption and cold-weather heating requirements [16], [25].

PIT VENTILATION SYSTEMS: DESIGN & OPERATING PRINCIPLES

The proportion of total building ventilation represented by pit fans varies seasonally due to the large range in wall fan operation between winter minimum and summer maximum ventilation. In winter, when wall fans operate at low rates to conserve heat, pit fans may represent 50–70% of total ventilation if operated continuously [15], [48]. This high proportion can create temperature control challenges and excessive heating costs. In summer, when wall fans operate at maximum capacity, the same pit fan rate may represent only 15–25% of total ventilation [1], [34]. Design guidelines typically recommend sizing pit ventilation to represent 25–40% of total capacity at average operating conditions, recognizing that this proportion will vary seasonally [4], [10].

Control strategies for pit ventilation range from simple continuous operation to sophisticated variable-speed systems coordinated with wall fan operation. Continuous operation at a fixed rate provides consistent air quality but consumes maximum energy and can create cold-weather problems [1], [34]. Time-based control, where pit fans operate at higher rates during daytime hours when workers are present and animals are more active, offers modest energy savings while maintaining protection during critical periods [34]. Temperature-based control adjusts pit ventilation in response to outdoor temperature, reducing rates during cold weather to minimize heating costs while maintaining minimum air quality standards [15], [48]. The most advanced systems employ variable-speed drives that continuously adjust pit fan speed in proportion to total building ventilation, maintaining consistent pressure relationships and emission capture efficiency across all operating conditions [17].

Recent research has explored machine-learning approaches to ventilation control that could optimize pit fan operation based on real-time conditions. Yeo and colleagues developed random forest models that predict indoor temperature and carbon dioxide concentrations with high accuracy ($R^2 \geq 0.848$ for temperature, $R^2 \geq 0.885$ for CO_2), providing a foundation for predictive control algorithms [24]. Wu and colleagues proposed data-driven decision models that integrate variable-speed drive outputs to set optimal fan speeds for energy-efficient ventilation in multi-floor pig buildings [31]. These approaches show promise for reducing energy consumption while maintaining air quality, but field validation at commercial scale remains limited, representing a significant research gap discussed in Section 9.

4. AIR QUALITY & GAS MANAGEMENT

The primary documented benefit of pit ventilation is substantial improvement in indoor air quality through source capture of ammonia and hydrogen sulfide before these gases enter the animal living space. Field measurements in commercial swine facilities have consistently demonstrated that properly designed pit ventilation systems capture 70–81% of total ammonia and hydrogen sulfide emissions despite representing only 25–40% of total building airflow, reflecting the spatial concentration of emission sources at the pit surface [1], [34], [41].

The landmark emission partitioning study conducted by Jacobson and colleagues in a commercial 2,000-head finishing facility in southern Minnesota provides the most comprehensive field data on pit ventilation effectiveness [34]. The study monitored a double-wide building for 45 days during late summer, with one 1,000-head room operating pit fans at 27 cfm per pig continuously and the other room operating at 27 cfm per pig at night and 43 cfm per pig during the day. Continuous measurements of ammonia and hydrogen sulfide concentrations at both pit and wall exhaust points, combined with airflow measurements, enabled calculation of emission rates from each pathway. Results demonstrated that the room with continuous 27 cfm per pig pit ventilation exhausted 70% of ammonia and 76% of hydrogen sulfide through pit fans, while the room with variable pit ventilation exhausted 75% of ammonia and 81% of hydrogen sulfide through pit fans during daytime operation [34]. Notably, increasing pit ventilation from 27 to 43 cfm per pig provided only marginal improvement in capture efficiency, suggesting diminishing returns above approximately 25–30 cfm per pig.

A subsequent study by the same research group extended these findings by sampling both pit and wall exhaust for a comprehensive suite of contaminants including ammonia, hydrogen sulfide, carbon dioxide, particulate matter, and odor [1], [41]. Results confirmed the high capture efficiency for gaseous contaminants, with pit exhaust accounting for the majority of emissions despite representing a minority of airflow. Odor measurements revealed that pit exhaust had substantially higher odor concentrations than wall exhaust, indicating that pit ventilation captures odorous compounds along with inorganic gases [1]. This finding has important implications for facilities facing community concerns about odor, as treating the concentrated pit exhaust stream with biofilters or other technologies can achieve substantial odor reduction more economically than treating total building exhaust.

Comparative studies of facilities with and without pit ventilation provide additional evidence of air quality benefits. Wilhelm and McKinney conducted continuous monitoring of temperature and gas levels in two similar swine buildings over two winter seasons, one equipped with pit ventilation and one without [59]. Ammonia and hydrogen sulfide concentrations were significantly higher in the building without pit ventilation, despite that building operating wall fans more frequently in an attempt to maintain acceptable air quality [59]. This finding demonstrates that source capture is more effective than increased dilution ventilation for controlling pit-source emissions, and that pit ventilation can actually reduce total fan operation time while improving air quality.

AIR QUALITY & GAS MANAGEMENT

The spatial distribution of contaminants within the barn is substantially altered by pit ventilation. Studies measuring gas concentrations at multiple heights and locations have documented that conventional wall-fan ventilation creates vertical gradients with highest concentrations near the floor and lower concentrations at ceiling height [7], [20], [36]. Pit ventilation reduces these gradients by preventing upward migration of gases from the pit, resulting in more uniform air quality throughout the barn volume [7], [36]. This improved uniformity has potential benefits for animal welfare, as pigs spend most of their time near the floor where concentrations are highest in conventionally ventilated facilities.

The concentrated nature of pit exhaust creates opportunities for targeted emission treatment that are not economically feasible with conventional ventilation systems. Biofilters, which use microbial degradation in organic media to remove ammonia and odorous compounds, are most effective when treating high-concentration, low-volume airstreams [4], [10], [47]. Treating pit exhaust with a biofilter requires a much smaller (and less expensive) biofilter than treating total building exhaust, making emission control economically viable for facilities facing regulatory requirements or community pressure. Danish experience with mandatory emission reduction has demonstrated the practical effectiveness of pit ventilation combined with biofilter treatment, achieving 50–70% reductions in ammonia emissions and substantial odor reduction [10], [47]. However, the economic and regulatory context in Denmark differs substantially from North American conditions, and the transferability of these results requires careful evaluation.

Integration of pit ventilation with other emission reduction strategies represents an emerging area of research. Recent studies have investigated the interaction between pit fan operation and bio-curtain systems, which spray water or treatment solutions to capture airborne contaminants. Halder and colleagues found that ammonia emission rates declined when exhaust fans operated at minimum speed, with greater reduction when bio-curtain spray was active, indicating that fan speed affects emission control system performance [24]. This finding suggests that variable-speed control of pit fans could enhance the effectiveness of complementary emission reduction technologies, though the mechanisms and optimal operating strategies require further investigation.

5. WORKER SAFETY

Worker safety represents one of the most compelling justifications for pit ventilation, particularly regarding protection from acute hydrogen sulfide exposure during manure agitation and chronic respiratory effects from prolonged exposure to ammonia and particulate matter. Hydrogen sulfide is an acutely toxic gas that can cause rapid unconsciousness and death at concentrations above 500–1,000 parts per million, levels that can develop within minutes during manure mixing in deep-pit facilities [2], [38], [45], [54], [57]. The occupational safety literature documents numerous fatalities in swine facilities associated with hydrogen sulfide release during pit pump-out, often involving multiple victims when rescuers enter the contaminated space without proper respiratory protection [67].

The mechanism of acute hydrogen sulfide release during manure agitation is well established. Hydrogen sulfide is produced by anaerobic bacteria in stored manure and accumulates in the liquid phase, with concentrations increasing over time as manure ages [35], [38], [44]. When manure is mechanically agitated for pump-out, the mixing action releases dissolved hydrogen sulfide into the air space above the liquid surface, causing rapid increases in airborne concentrations [2], [38], [45], [54]. The rate and magnitude of release depend on multiple factors including manure temperature, storage duration, mixing intensity, and ventilation rate, but increases of two to three orders of magnitude within minutes have been documented [2], [38], [57].

The comprehensive study by Patni and Clarke provides detailed documentation of hydrogen sulfide dynamics during slurry mixing in 12 commercial swine barns over a two-year period [2], [45], [54]. Continuous monitoring using electrochemical sensors revealed that hydrogen sulfide concentrations were at acceptable levels when manure was undisturbed, but immediate and very rapid release occurred at the start of mixing [2], [45], [54]. In one case, concentrations reached lethal levels despite the presence of ventilation, demonstrating that conventional wall-fan ventilation alone may be insufficient to prevent dangerous conditions during agitation [2], [45], [54]. The study found that well-functioning pit exhaust fans, combined with avoiding splashing and free-falling of slurry in the pit, substantially reduced hydrogen sulfide concentrations during mixing operations [2], [45], [54]. This finding provides strong evidence that pit ventilation offers critical protection during the highest-risk operations in swine facilities.

The practical implications for worker safety are clear. Pit ventilation should be operated at maximum capacity during all manure agitation and pump-out operations to provide maximum dilution and removal of released gases [2], [8], [45], [50], [54], [68]. Workers should be trained to recognize the hazards of hydrogen sulfide exposure and to evacuate immediately if symptoms of exposure occur. Continuous gas monitoring with audible alarms should be employed during pump-out operations to provide early warning of dangerous conditions. Even with pit ventilation operating, proper confined space entry procedures must be followed if pit entry is necessary, including atmospheric testing, continuous forced ventilation, and standby personnel with appropriate rescue equipment [43], [60].

WORKER SAFETY

Beyond acute hazards, pit ventilation reduces chronic occupational exposure to ammonia and particulate matter, potentially improving long-term respiratory health outcomes for swine workers. Epidemiological studies have documented elevated rates of respiratory symptoms, bronchial hyperresponsiveness, and accelerated lung function decline among workers in swine confinement facilities [63], [66]. While these studies have not specifically isolated the effect of pit ventilation, the substantial reductions in ammonia concentrations achieved with pit fans would be expected to reduce chronic respiratory effects. Ammonia is a respiratory irritant that damages airway epithelium and increases susceptibility to respiratory infections, with occupational exposure limits typically set at 25 parts per million for an 8-hour time-weighted average [18], [51]. Maintaining concentrations below these limits is challenging in swine facilities without pit ventilation, particularly during winter when ventilation rates are minimized to conserve heat [14], [51].

The interaction between pit ventilation and emergency response procedures deserves emphasis. While pit ventilation substantially reduces the risk of hazardous gas accumulation, it does not eliminate the need for proper safety protocols. Power outages, fan failures, or control system malfunctions can rapidly lead to dangerous conditions, particularly during manure agitation [59]. Facilities should have backup power for pit fans or emergency procedures for evacuating animals and personnel if ventilation is lost during critical operations. Gas detection systems with audible alarms provide an additional layer of protection by alerting workers to developing hazards before concentrations reach immediately dangerous levels [53].

6. ANIMAL WELFARE & PRODUCTION PERFORMANCE

The effects of pit ventilation on animal welfare and production performance are less extensively documented than air quality and worker safety outcomes, but available evidence suggests modest benefits for respiratory health and thermal comfort under specific conditions. Ammonia is a respiratory irritant that damages the epithelial lining of pigs' airways at concentrations commonly encountered in swine facilities, increasing susceptibility to respiratory disease and potentially impairing growth performance [18]. Recommended maximum concentrations for swine housing typically range from 10 to 25 parts per million for chronic exposure, though these guidelines are based primarily on human occupational health standards rather than controlled animal studies [18]. By reducing ammonia concentrations in the animal living space, pit ventilation may help maintain better respiratory health in the herd, though direct evidence linking pit ventilation to reduced disease incidence is limited.

Respiratory health effects of ammonia exposure in pigs have been documented in controlled chamber studies and observational research in commercial facilities. Pickrell and colleagues investigated endotoxin, ammonia, and dust exposure in swine confinement buildings, finding associations between air quality parameters and respiratory pathology [17]. Charavaryamath and Singh reviewed pulmonary effects of exposure to pig barn air, documenting inflammatory responses and structural changes in airways associated with chronic exposure to ammonia and particulate matter [69]. These findings suggest that improvements in air quality achieved through pit ventilation could translate to better respiratory health outcomes, though the magnitude of benefits likely depends on baseline air quality and the degree of improvement achieved.

The interaction between pit ventilation and thermal comfort is complex and varies seasonally. In warm weather, pit fans contribute to total building ventilation and help maintain adequate air exchange rates for heat removal [9]. However, the contribution of pit ventilation to cooling is modest compared to wall fans, as pit airflow represents only 25–40% of total ventilation and does not directly increase air velocity in the animal zone. In cold weather, pit ventilation can complicate temperature control by increasing total ventilation beyond what is needed for heating, potentially creating drafts and cold stress if not properly managed [15], [48]. Simulation studies of winter ventilation in farrowing facilities have shown that pit ventilation increases heating requirements and can make it more difficult to maintain the high temperatures required for newborn piglets [15], [48].

Direct evidence linking pit ventilation to improved growth rates or feed efficiency is limited and inconclusive. Comparative studies of different manure management systems have generally found no significant differences in animal performance attributable to pit ventilation alone [32], [46], [61]. However, these studies were not specifically designed to isolate the effects of pit ventilation from other management factors, and the absence of detected differences may reflect insufficient statistical power or confounding variables rather than true lack of effect. The air quality improvements achieved with pit fans would be expected to support better performance, particularly

in facilities where ammonia concentrations would otherwise exceed recommended limits, but quantifying these benefits requires controlled studies with adequate replication and careful attention to confounding factors.

Thermal comfort interactions deserve particular attention in farrowing facilities, where the conflicting temperature requirements of sows and piglets create challenging ventilation management scenarios. Sows prefer relatively cool temperatures (60–65°F) while newborn piglets require warm environments (85–95°F), typically provided by supplemental heat lamps in the creep area [15], [48]. Pit ventilation increases total building ventilation, making it more difficult to maintain high temperatures and potentially increasing heating costs substantially [15], [48]. Simulation modeling by Park and colleagues demonstrated that operating pit fans in winter farrowing facilities increased heating costs by 15–30% depending on outdoor temperature and pit ventilation rate [15], [48]. These findings suggest that pit ventilation may be less economically attractive in farrowing facilities than in finishing or gestation facilities, particularly in cold climates.

7. ECONOMIC & OPERATIONAL CONSIDERATIONS

Economic viability represents a critical factor in adoption decisions for pit ventilation systems, with producers weighing substantial upfront capital costs and ongoing operating expenses against air quality, safety, and potential regulatory compliance benefits. Capital costs for pit ventilation include additional fans and motors, ductwork and pit modifications, electrical infrastructure, and engineering design services. While specific costs vary with facility size, configuration, and regional labor rates, adding pit ventilation to an existing building typically represents a significant capital expense, and incorporating pit ventilation in new construction adds an estimated 10–20% premium to ventilation system costs compared to conventional wall-fan-only designs [4], [10].

Energy consumption represents the largest ongoing operating cost for pit ventilation systems. Pit fans operate in addition to, not instead of, wall ventilation fans, increasing total building energy consumption. The magnitude of this increase depends on pit fan sizing, operating strategy, and seasonal ventilation requirements. Continuous operation of pit fans sized at 25–30 cubic feet per minute per pig adds substantial electrical load, particularly in large finishing facilities housing 1,000–2,500 head [12]. Variable-speed drive technology offers potential for energy savings by modulating pit fan speed in response to changing ventilation needs, but quantified energy savings from variable-speed pit fans in commercial swine facilities have not been reported in the peer-reviewed literature, representing a significant research gap discussed in Section 9 [12].

Heating costs represent an additional and often substantial operating expense associated with pit ventilation, particularly in cold climates. Running pit fans in winter increases total ventilation rate, requiring more supplemental heat to maintain barn temperature. The magnitude of heating cost

increases depends on outdoor temperature, pit ventilation rate, and building thermal characteristics. Simulation modeling of winter ventilation in Midwestern farrowing facilities found that operating pit fans increased heating costs by 15–30% depending on outdoor temperature and pit ventilation rate [15], [48], [58]. These increases are most pronounced in farrowing facilities where high temperatures must be maintained for newborn piglets, but are also significant in finishing and gestation facilities during extended cold periods [15], [48], [58].

Cold-climate operation presents the most significant practical challenge for pit ventilation systems in northern swine-producing regions. Exhaust air from the pit is warm and humid, and when this air contacts cold surfaces in the exhaust duct or at the fan discharge, condensation and freezing can occur [7], [15], [36], [48]. Ice buildup can block exhaust ducts, damage fans, and create safety hazards from falling ice. Research on wintertime factors affecting contaminant distribution in swine facilities has documented that pit ventilation systems are particularly vulnerable to freezing problems [7], [15], [36], [48]. Design strategies to mitigate freezing include insulated exhaust ducts, heat recovery systems to capture warmth from pit exhaust, intermittent operation strategies that balance air quality and temperature control, and discharge configurations that prevent ice buildup near the building [26]. However, these solutions add complexity and cost to the system.

Maintenance requirements for pit ventilation systems exceed those for conventional wall-fan-only systems due to the harsh pit environment and accessibility challenges. Pit fans and exhaust ducts are exposed to corrosive gases (ammonia, hydrogen sulfide) and high humidity, leading to accelerated corrosion and dust accumulation [33], [52]. Regular inspection and cleaning are essential to maintain airflow capacity and prevent premature equipment failure, but performing maintenance on pit fans and ductwork often requires entering or working near the manure pit, creating safety concerns and requiring proper confined space entry procedures [28], [43], [60]. The harsh pit environment reduces equipment lifespan compared to wall fans, with pit fans, motors, and ductwork potentially requiring replacement more frequently and increasing long-term maintenance costs [33], [52].

Long-term economic analyses comparing total costs and benefits of pit ventilation over the facility lifespan are notably absent from the published literature, representing a critical research gap discussed in Section 9. Available cost information is limited to capital cost estimates and short-term operating cost measurements, without comprehensive payback analyses that account for all costs and benefits over time. This absence of economic data makes it difficult for producers to make fully informed investment decisions and represents a priority area for future research. The economic case for pit ventilation is strongest in situations where regulatory requirements mandate emission control, where community relations concerns justify investment in odor reduction, or where worker safety considerations outweigh purely economic factors [4], [5], [10], [30], [47].

8. DESIGN & MANAGEMENT RECOMMENDATIONS

Successful implementation of pit ventilation requires careful attention to system design, integration with overall facility ventilation, and operational management across varying seasonal conditions. This section synthesizes evidence-based recommendations for producers and designers considering pit ventilation systems, organized by design phase and operational considerations.

Ventilation Rate Guidelines

Research evidence supports designing pit ventilation systems for 25–30 cubic feet per minute per pig as a target rate, representing approximately 30–40% of total building ventilation capacity under average operating conditions [1], [4], [34]. Field studies have demonstrated that rates below 20–25 cfm per pig may be insufficient to maintain negative pressure throughout the pit and prevent updrafting of gases, while rates substantially above 30–35 cfm per pig provide diminishing returns in emission capture efficiency while increasing energy costs and cold-weather challenges [34]. The proportion of total ventilation represented by pit fans will vary seasonally, potentially reaching 50–70% of total ventilation in winter when wall fans operate at minimum rates and dropping to 15–25% in summer when wall fans operate at maximum capacity [1], [15], [34], [48]. Designers should verify that this seasonal variation does not create temperature control problems in winter or inadequate pit ventilation in summer.

Fan Placement and System Configuration

For buildings longer than 150 feet, multiple pit exhaust points distributed along the pit length are recommended to ensure uniform gas removal throughout the pit space [16], [19], [25]. Single-point exhaust at one building end creates uneven airflow patterns and may leave dead zones with poor gas capture in distant regions [16], [25]. Computational fluid dynamics modeling has demonstrated that exhaust point spacing significantly affects system performance, with optimal spacing depending on pit geometry and ventilation rate [16], [25]. Wall-mounted fans with horizontal ductwork extending into the pit to create distributed collection points represent the most common and generally effective configuration in North American facilities [1], [34].

Inlet configuration should be designed to provide adequate fresh air entry into the pit without creating excessive drafts in the animal zone. The simplest approach relies on airflow through the slatted floor itself, which requires no additional infrastructure but provides limited control over inlet air distribution [19], [27]. Dedicated pit inlets offer improved control but add cost and complexity, and may be justified in facilities where precise control of pit airflow patterns is critical [27]. Regardless of inlet configuration, designers should verify that adequate inlet area is provided to prevent excessive pressure drop and ensure proper airflow distribution.

DESIGN & MANAGEMENT RECOMMENDATIONS

Pressure Cascade and System Integration

Maintaining proper pressure relationships is critical for effective pit ventilation operation. The pit should operate at negative pressure relative to the barn, and the barn should operate at negative pressure relative to outdoors, creating a pressure cascade that ensures air flows in the intended direction [4], [27]. If pit ventilation is excessive relative to wall ventilation, the barn may become positively pressurized, causing uncontrolled air leakage and compromising inlet air distribution [4]. Designers should calculate expected pressure relationships across the range of seasonal operating conditions and verify that proper pressure hierarchy is maintained. Integration with the barn's overall ventilation system requires coordinated control of pit and wall fans to maintain appropriate pressure relationships and ventilation rates across all seasons [3], [11].

Advanced Control Technologies

Recent research on variable-speed drive technology and machine-learning control algorithms offers promising pathways to improved energy efficiency, though field validation at commercial scale remains limited. Variable-speed drives enable continuous modulation of pit fan speed in response to changing ventilation needs, potentially reducing energy consumption compared to on-off control while maintaining consistent air quality [17]. Yeo and colleagues demonstrated that random forest machine-learning models can predict indoor temperature and carbon dioxide concentrations with high accuracy ($R^2 \geq 0.85$), providing a foundation for predictive control algorithms that anticipate ventilation needs and optimize fan operation [24]. Wu and colleagues proposed data-driven decision models that integrate variable-speed drive outputs to set optimal fan speeds for energy-efficient ventilation [31]. These approaches show substantial promise, but producers considering these technologies should be prepared for a degree of uncertainty and should work with experienced controls specialists to ensure proper implementation.

Cold-Weather Design Features

For facilities in cold climates, specific design features are essential to prevent freezing and manage heating costs. Insulated exhaust ducts reduce condensation and freezing risk by maintaining higher surface temperatures [15], [48]. Discharge configurations that direct exhaust away from the building and prevent ice accumulation near walls or walkways improve safety and reduce maintenance [15], [48]. Heat recovery systems that capture warmth from pit exhaust and transfer it to incoming ventilation air can partially offset increased heating costs, though the economic viability depends on climate severity and energy costs [26]. Intermittent operation strategies that reduce pit ventilation during the coldest periods may be necessary to maintain acceptable heating costs, though producers must balance energy savings against air quality and safety considerations [15], [48].

DESIGN & MANAGEMENT RECOMMENDATIONS

Monitoring, Maintenance, and Operational Protocols

Installing monitoring systems to track pit fan operation and air quality is strongly recommended, particularly given the safety-critical nature of pit ventilation and the difficulty of visually confirming proper operation of fans located beneath the floor [3]. Airflow sensors verify that pit fans are moving adequate air and can alert operators to fan failures or duct blockages [3]. Gas sensors that continuously monitor ammonia and hydrogen sulfide concentrations in the barn and pit provide feedback on system effectiveness and early warning of hazardous conditions [53]. Alarm systems that alert operators to fan failures or elevated gas levels are particularly important during manure agitation when dangerous conditions can develop rapidly [53].

Regular maintenance is essential to ensure continued proper operation. Pit fans and ductwork should be inspected at least quarterly for corrosion, dust accumulation, and proper operation, with cleaning or component replacement as needed [33], [52]. Selecting corrosion-resistant materials and coatings for all pit fans, motors, and ductwork substantially extends equipment life in the harsh pit environment [33], [52]. Pit fans should be operated at maximum capacity during all manure agitation and pump-out operations to provide maximum protection against hydrogen sulfide release [2], [8], [45], [50], [54], [68]. Emergency procedures for power outages or ventilation system failures during manure agitation should be established and practiced, including rapid animal and personnel evacuation if necessary. Backup power for pit fans should be available for use during critical operations.

9. RESEARCH GAPS & FUTURE DIRECTIONS

Despite four decades of research on pit ventilation systems in swine facilities, significant knowledge gaps remain that limit producers' ability to make fully informed decisions and constrain optimization of system design and operation. This section identifies six critical research gaps confirmed through systematic review of the 2020–2026 literature and discusses their implications for producers and future research priorities.

Energy Savings Quantification

No published study has directly quantified percent energy savings from variable-speed drive equipped pit fans in commercial swine finishing buildings. While recent research has demonstrated that variable-speed drives enable finer flow control compared to on-off systems and that demand-controlled ventilation can reduce energy consumption in livestock settings, quantified savings specific to pit fans in swine facilities are absent from the literature [12]. This gap is particularly significant given that energy costs represent the largest ongoing operating expense for pit ventilation and that variable-speed technology is increasingly promoted as an energy-saving solution. Producers considering variable-speed pit fans must make investment decisions without reliable data on expected payback periods or return on investment. Future research should conduct controlled field trials in commercial finishing facilities comparing energy consumption of variable-speed versus fixed-speed pit fans across full production cycles and varying seasonal conditions.

Machine-Learning Control Validation

Machine-learning driven demand control algorithms show promise in prediction accuracy but lack validated field trials at commercial scale. Yeo and colleagues demonstrated that random forest models can predict indoor temperature and carbon dioxide with high accuracy ($R^2 \geq 0.85$), and Wu and colleagues proposed data-driven decision models for setting optimal fan speeds, but neither study reported implementation and validation in operating commercial facilities [24], [31]. The gap between algorithm development and field validation under real-world conditions with variable weather, changing animal populations, and practical operational constraints is substantial. Producers cannot confidently adopt machine-learning control systems without evidence that they perform reliably under commercial conditions and deliver promised energy savings and air quality benefits. Future research should implement and validate machine-learning control algorithms in commercial facilities over extended periods, measuring energy consumption, air quality, animal performance, and system reliability compared to conventional control approaches.

RESEARCH GAPS & FUTURE DIRECTIONS

Facility Type Performance Data

Limited data exist on pit fan performance across different facility types, with the vast majority of published research focused on finishing barns. Gestation, farrowing, and nursery facilities have different ventilation requirements, thermal management challenges, and manure characteristics that may affect pit ventilation performance, but systematic studies comparing pit fan effectiveness across facility types are lacking [4]. Farrowing facilities present particular challenges due to conflicting temperature requirements of sows and piglets and the need to maintain high temperatures that increase heating costs when pit ventilation is operated [15], [48]. The absence of facility-specific performance data means that design recommendations developed for finishing barns may not be optimal for other facility types. Future research should conduct systematic studies of pit ventilation performance in gestation, farrowing, and nursery facilities, measuring emission capture efficiency, energy consumption, air quality outcomes, and economic performance.

Cold-Climate Operational Protocols

Cold-climate wintertime operation protocols lack evidence-based guidelines, despite freezing and heating cost challenges being identified as primary barriers to adoption in northern swine-producing regions. While simulation studies have quantified heating cost increases associated with winter pit fan operation and documented freezing risks, systematic research on operational strategies to mitigate these challenges is limited [15], [48]. Questions remain about optimal pit ventilation rates during cold weather, effectiveness of intermittent operation strategies, performance of heat recovery systems, and design features that minimize freezing while maintaining adequate air quality and safety. Future research should conduct winter-long field studies in cold-climate facilities testing alternative operational strategies, measuring heating costs, freezing incidents, air quality, and worker safety outcomes to develop evidence-based cold-weather management protocols.

Long-Term Economic Analysis

Long-term economic payback analyses are absent from the literature, making it difficult for producers to evaluate the financial viability of pit ventilation investments. Available economic information is limited to capital cost estimates and short-term operating cost measurements, without comprehensive analyses that account for all costs and benefits over the facility lifespan [4], [10]. A complete economic analysis would include capital costs, energy costs, maintenance costs, equipment replacement costs, potential benefits from improved animal performance, reduced veterinary costs, improved worker health and retention, and avoided regulatory compliance costs. The time horizon for analysis should span the expected facility lifespan (15–25 years) and should account for uncertainty in future energy prices, regulatory requirements, and market conditions. Future research should conduct comprehensive economic analyses of pit ventilation systems across a range of facility types, climates, and regulatory contexts using actual cost and performance data from commercial operations.

RESEARCH GAPS & FUTURE DIRECTIONS

Emission Treatment Integration

Integration of pit exhaust treatment technologies with variable-speed controlled fans has not been studied, despite the potential for synergistic benefits. Biofilters and other emission treatment technologies are most effective when treating consistent airflow at optimal loading rates, but variable-speed pit fans by definition produce varying airflow that may challenge treatment system performance [4], [10], [47]. Questions remain about how to design and control integrated systems that optimize both ventilation energy efficiency and emission treatment effectiveness, whether treatment systems should be sized for peak or average pit fan airflow, and how control algorithms should coordinate pit fan speed with treatment system operation. Future research should investigate integrated pit ventilation and emission treatment systems, measuring both energy consumption and emission reduction effectiveness across varying operating conditions to develop design and control guidelines for optimized integrated systems.

10. CONCLUSION

Pit ventilation systems represent a proven technology for improving air quality, enhancing worker safety, and enabling targeted emission control in swine facilities with deep-pit manure storage. Four decades of research, including controlled field trials in commercial facilities, computational modeling, and operational studies, have established that properly designed pit ventilation systems capture 70–81% of ammonia and hydrogen sulfide emissions at the source despite representing only 25–40% of total building airflow [1], [34], [41]. This disproportionate capture efficiency reflects the spatial concentration of emission sources at the pit surface and the effectiveness of source-capture ventilation in intercepting gases before they enter the animal living space. The concentrated nature of pit exhaust creates opportunities for economically viable emission treatment using biofilters or other technologies, making pit ventilation an enabling technology for facilities facing regulatory requirements or community pressure for emission control [4], [10], [47].

Worker safety benefits provide a compelling justification for pit ventilation, particularly regarding protection from acute hydrogen sulfide exposure during manure agitation. Field studies have documented that hydrogen sulfide concentrations can reach lethal levels within minutes during manure mixing, and that well-functioning pit exhaust fans substantially reduce concentrations during these critical operations [2], [45], [54]. The occupational safety literature documents numerous fatalities associated with hydrogen sulfide exposure during pit pump-out, underscoring the importance of effective ventilation for worker protection [67]. Beyond acute hazards, pit ventilation reduces chronic exposure to ammonia and particulate matter, potentially improving long-term respiratory health outcomes for swine workers, though direct evidence of health benefits remains limited [18], [51], [62], [64].

CONCLUSION

However, pit ventilation systems impose substantial costs and operational challenges that must be carefully weighed against benefits. Capital costs add an estimated 10–20% premium to ventilation system costs in new construction, with higher costs for retrofitting existing facilities [4], [10]. Energy consumption increases due to operation of pit fans in addition to wall fans, with the magnitude depending on system sizing and operating strategy [12]. Heating costs increase by 15–30% in cold climates due to increased winter ventilation rates [15], [48], [58]. Cold-weather operation presents significant challenges including freezing risks and temperature control difficulties, requiring careful design and management to prevent operational problems [7], [15], [36], [48]. Maintenance requirements exceed those for conventional systems due to the harsh pit environment and accessibility challenges, with accelerated equipment corrosion and the need for confined space entry procedures for maintenance [28], [33], [43], [52], [60].

Recent advances in variable-speed drive technology and machine-learning control algorithms offer promising pathways to improved energy efficiency and optimized operation, but field validation at commercial scale remains limited [12], [17], [24], [31]. The research gaps identified in Section 9; including absence of quantified energy savings data, lack of validated machine-learning control systems, limited facility-type-specific performance data, absence of evidence-based cold-climate protocols, lack of long-term economic analyses, and no research on integrated emission treatment systems; represent significant barriers to optimal implementation and informed decision-making. Addressing these gaps should be a priority for agricultural engineering research programs, with emphasis on field studies in commercial facilities that generate practical, actionable information.

For producers who decide to implement pit ventilation, success depends on proper system design, careful integration with overall facility ventilation, and diligent operational management. Design recommendations include sizing pit ventilation for 25–30 cubic feet per minute per pig, installing multiple exhaust points in buildings longer than 150 feet, maintaining proper pressure cascade relationships, incorporating cold-weather design features in northern climates, and installing monitoring systems to track performance and alert operators to problems [1], [4], [16], [19], [25], [34]. Pit ventilation should be viewed as one component of a comprehensive approach to air quality management that also includes proper facility design, appropriate stocking density, good manure management practices, and regular maintenance of all ventilation equipment. When properly implemented and managed, pit ventilation can make meaningful contributions to healthier, safer, and more environmentally responsible swine production. However, producers must carefully evaluate whether the substantial benefits justify the significant costs and operational challenges in their specific circumstances.

KEY PERFORMANCE STATISTICS

Emission Captrue: NH_3	**70–81% of total ammonia captured via pit exhaust despite representing only 25–40% of airflow**
Emission Captrue: H_2S	**76–81% of total hydrogen sulfide captured at source before entering animal zone**
Design Target	**25–30 cfm per pig; multiple exhaust points required in buildings >150 ft**
Seasonal Range	**15–25% of total ventilation (summer) to 50–70% (winter)**
Capital Cost Premium	**10–20% above conventional ventilation-only systems in new construction**
Heating Cost Increase	**15–30% increase in cold climates; highest impact in farrowing facilities**
ML Control Accuracy	**$R^2 \geq 0.848$ (temperature) and $R^2 \geq 0.885$ (CO_2) with random forest models [Yeo et al., 2023]**

TABLE 1. Key Field Studies of Pit Ventilation Performance in Swine Facilities

Author(s) & Year	Facility Type	Pit Fan Rate (cfm/pig)	NH_3 Capture (%)	H_2S Capture (%)	Key Finding
Jacobson et al., 2005 [34]	Deep-pit finishing, 1,000 head	27 (continuous)	70	76	Pit exhaust captured majority of emissions despite ~30% of total airflow; established emission partitioning methodology.
Jacobson et al., 2005 [34]	Deep-pit finishing, 1,000 head	27 night / 43 day	75	81	Higher daytime pit ventilation provided only marginal improvement over continuous 27 cfm/pig.
Jacobson et al., 2007 [1], [41]	Deep-pit finishing	27	70+	76+	Extended study including PM and odor; confirmed high capture efficiency for multiple contaminants.
Wilhelm & McKinney, 2001 [59]	Finishing, comparative	Not specified	Not quantified	Not quantified	Building with pit ventilation had significantly lower NH_3 and H_2S despite less wall fan operation.
Patni & Clarke, 2003 [2], [45], [54]	12 commercial barns	Variable	Not quantified	Substan-tial reduction	Pit fans critical for H_2S control during agitation; lethal concentrations reached in one case without adequate pit ventilation.
Saha et al., 2010	Fattening pig room	Variable (partial pit)	30-50	Not measured	Partial pit ventilation reduced indoor NH_3; effectiveness varied with pit ventilation proportion.
Rong, 2020 [6], [40]	Experimental pig house	Variable	Improved removal	Not measured	Pit ventilation increased NH_3 removal ratio and mass transfer coefficients from pit surface.
Bjerg et al., 2014 [39]	Pig housing (CFD modeling)	Variable	Improved capture	Not measured	CFD modeling showed improved performance with optimized pit exhaust design.

TABLE 2. Research Gaps and Implications for Producers

Research Gap	Implication for Producers
No quantified energy savings from VSD-equipped pit fans	Producers considering variable-speed drives cannot reliably estimate payback periods or return on investment; must make decisions without data on expected energy savings.
ML-driven control lacks commercial-scale validation	Producers cannot confidently adopt machine-learning control systems without evidence of reliable performance under real-world conditions; potential benefits remain theoretical.
Limited data on facility types beyond finishing	Design recommendations developed for finishing barns may not be optimal for gestation, farrowing, or nursery facilities; producers must extrapolate from limited data.
Absence of evidence-based cold-climate protocols	Producers in northern regions must rely on trial-and-error or conservative designs that may sacrifice air quality benefits to avoid freezing and heating cost problems.
No long-term economic payback analyses	Producers cannot evaluate financial viability over facility lifespan; must make major capital decisions without clear understanding of expected returns.
No research on VSD integration with emission treatment	Producers cannot confidently combine variable-speed pit fans with biofilters or other treatment systems; may forego energy savings to maintain treatment performance.

TABLE 3. Benefits and Drawbacks of Pit Ventilation Systems

Benefits	Drawbacks
Captures 70–81% of NH_3 and H_2S at source before entering barn	Capital cost premium of 10–20% for new construction, higher for retrofits
Substantially improves indoor air quality for animals and workers	Increases energy consumption due to additional fan operation
Critical protection during manure agitation when lethal H_2S can develop	Heating costs increase 15–30% in cold climates due to increased winter ventilation
Enables economical emission treatment with biofilters (concentrated exhaust)	Freezing risks in cold weather require careful design and management
Reduces chronic worker exposure to ammonia and particulate matter	Temperature control challenges, particularly in winter and farrowing facilities
Creates more uniform air quality throughout barn (reduces vertical gradients)	Maintenance challenges due to harsh pit environment and accessibility
Facilitates regulatory compliance where emission control is required	Equipment corrosion and reduced lifespan in corrosive pit atmosphere
Improves community relations through odor and emission reduction	Performance monitoring difficult (fans operate out of sight beneath floor)

REFERENCES

Jacobson, L.D., Hetchler, B.P., & Schmidt, D.R. (2007). Sampling pit and wall emission for H2S, NH3, CO2, PM, & odor from deep-pit pig finishing facilities. https://doi.org/10.13031/2013.23886

Patni, N.K., & Clarke, S.P. (2003). Gaseous Emissions in Swine Barns and During Slurry Mixing in Sub-Floor Pits. https://doi.org/10.13031/2013.14099

Nicolai, R.E., & Hoff, S.J. (2003). Ventilation requirements to prevent pit air up-drafting in a swine finishing barn. https://doi.org/10.13031/2013.15465

Zhang, G., Bjerg, B., & Zong, C. (2017). Partial Pit Exhaust Improves Indoor Air Quality and Effectiveness of Air Cleaning in Livestock Housing: A Review. https://doi.org/10.13031/AEA.11751

Miller, G.Y., Huang, H., Maghirang, R., Funk, T., Robert, M., & Zhang, Y. (n.d.). System influences on ammonia and hydrogen sulfide concentrations inside mechanically ventilated swine finishing buildings in illinois. https://doi.org/10.13031/2013.18395

Rong, L. (2020). Effect of partial pit exhaust ventilation system on ammonia removal ratio and mass transfer coefficients from different emission sources in pig houses. https://doi.org/10.1016/J.ENBENV.2020.04.006

Saha, C.K., Zhang, G., Kai, P., & Bjerg, B. (2010). Effects of a partial pit ventilation system on indoor air quality and ammonia emission from a fattening pig room. https://doi.org/10.1016/J.BIOSYSTEMSENG.2009.11.006

Hoff, S.J., Bundy, D.S., Nelson, M.A., Zelle, B.C., Jacobson, L.D., Heber, A.J., Ni, J., Zhang, Y., Koziel, J.A., & Beasley, D.B. (2006). Emissions of ammonia, hydrogen sulfide, and odor before, during, and after slurry removal from a deep-pit swine finisher.. https://doi.org/10.1080/10473289.2006.10464472

Harmon, J.D., Brumm, M.C., Jacobson, L.D., Pohl, S.H., Stender, D.R., & Stowell, R.R. (2012). Field Performance Evaluation of a Ventilation System: A Swine Case Study. https://doi.org/10.13031/2013.41342

Zhang, G., & Zong, C. (2014). An engineering approach for effective cleaning exhaust air from livestock housing - A Review of Danish experiences of using partial pit air exhaust.

Harmon, J.D., Brumm, M.C., Jacobson, L.D., Pohl, S.H., Stender, D.R., & Stowell, R.R. (2012). Field Performance Evaluation of a Ventilation System: A Swine Case Study. https://doi.org/10.13031/2013.41342

Barber, E., & Classen, H. (n.d.). Energy use in the production and housing of poultry and swine–an overview.

Rong, L., & Wang, X. (2023). Smart ventilation in confined animal buildings. https://doi.org/10.1007/978-3-031-24861-0_150

Predicala, B.Z., Maghirang, R.G., Jerez, S.B., Urban, J.E., & Goodband, R.D. (2000). Air quality in swine-finishing barns.. https://doi.org/10.4148/2378-5977.6583

Park, J.H., Park, J.H., Peters, T.M., Altmaier, R., Jones, S., Gassman, R., & Anthony, T.R. (2017). Simulation of Air Quality and Operating Cost to Ventilate Swine Farrowing Facilities in the Midwest U.S. During Winter. https://doi.org/10.13031/TRANS.11784

Bjerg, B. (2011). CFD Analyses of Methods to Improve Air Quality and Efficiency of Air Cleaning in Pig Production.. https://doi.org/10.5772/19302

Shin, H., Jo, S., & Kim, S. (n.d.). Optimal Control of Ventilation Fan in Smart Farm Using EnergyPlus. https://doi.org/10.7840/kics.2021.46.12.2411

Pickrell, J.A. (1991). Hazards in confinement housing--gases and dusts in confined animal houses for swine, poultry, horses and humans..

REFERENCES

Nicolai, R.E., & Hoff, S.J. (2003). Ventilation requirements to prevent pit air up-drafting in a swine finishing barn. https://doi.org/10.13031/2013.15465

Peters, T.M., Anthony, T.R., Taylor, C., Altmaier, R., Anderson, K., & O'Shaughnessy, P.T. (2012). Distribution of Particle and Gas Concentrations in Swine Gestation Confined Animal Feeding Operations. https://doi.org/10.1093/ANNHYG/MES050

Pickrell, J.A. (1991). Hazards in confinement housing--gases and dusts in confined animal houses for swine, poultry, horses and humans..

Thoma, G., Boles, P., Leh, M., & Sandefur, H. (n.d.). A Life Cycle Analysis of Water Use in US Pork Production.

Kang, D.Y., Moon, B.E., Kang, M.Y., Kook, J., Deb, N.C., Tamrakar, N., Arulmozhi, E., & Kim, H.T. (2025). Analysis of pig tendencies to stay specific sections within the pig barn according to environmental parameters and facilities features. https://doi.org/10.3390/agriculture15121282

Yeo, U., Jo, S., Kim, S., Park, D., Jeong, D., Park, S., Shin, H., & Kim, R. (2023). Applicability of Machine-Learned Regression Models to Estimate Internal Air Temperature and CO2 Concentration of a Pig House. https://doi.org/10.3390/agronomy13020328

Bjerg, B., Zhang, G., & Kai, P. (2008). CFD Investigation of a Partly Pit Ventilation System as Method to Reduce Ammonia Emission from Pig Production Units. https://doi.org/10.13031/2013.25479

Reeve, K.A., Peters, T.M., & Anthony, T.R. (2013). Wintertime factors affecting contaminant distribution in a swine farrowing room.. https://doi.org/10.1080/15459624.2013.777303

Nicolai, R.E., & Hoff, S.J. (2003). Ventilation requirements to prevent pit air up-drafting in a swine finishing barn. https://doi.org/10.13031/2013.15465

Jacobson, L., Pohl, S., & Bickert, W. (1978). Troubleshooting swine ventilation systems.

Pickrell, J.A. (1991). Hazards in confinement housing--gases and dusts in confined animal houses for swine, poultry, horses and humans..

Miller, G.Y., Huang, H., Maghirang, R., Funk, T., Robert, M., & Zhang, Y. (n.d.). System influences on ammonia and hydrogen sulfide concentrations inside mechanically ventilated swine finishing buildings in illinois. https://doi.org/10.13031/2013.18395

Wu, J., Li, J., & Liu, Z. (2025). Data-Based Decision-Making Model for Ventilation Control and Energy-Saving Strategies in Multi-Floor Pig Building. https://doi.org/10.2139/ssrn.5295303

Choi, Y., Ha, D., Lee, S., & Kim, D. (2022). Effect of aerobically treated manure on odorous material emissions from a swine finishing barn equipped with a continuous pit recirculation system. https://doi.org/10.5713/ab.21.0135

Ni, J., Liu, S., Lopes, I.M., Xie, Q., Zheng, P., & Diehl, C.A. (2017). Monitoring, modeling, and characterizing single-speed ventilation fans for an animal building. https://doi.org/10.1016/J.BUILDENV.2017.03.036

Jacobson, L.D., Janni, K.A., Hetchler, B.P., & Schmidt, D.R. (2005). Partitioning of Ammonia and Hydrogen Sulfide Emissions Into Pit and Wall Exhaust Fractions for a Deep-Pit Pig Finishing Barn. https://doi.org/10.13031/2013.19834

Arogo, J. (n.d.). Hydrogen sulfide emission and control parameters from stored liquid swine manure.

REFERENCES

Reeve, K.A., Peters, T.M., & Anthony, T.R. (2013). Wintertime factors affecting contaminant distribution in a swine farrowing room.. https://doi.org/10.1080/15459624.2013.777303

Janni, K.A., Jacobson, L.D., & Hetchler, B.P. (2008). Three-zone model of ammonia and hydrogen sulfide in a deep-pit swine finishing barn.. https://doi.org/10.13031/2013.25503

Seok, J. (n.d.). Assessment of Hydrogen Sulfide and Ammonia Concentrations in Swine, Poultry, Cattle Farms.

Bjerg, B., Riis, A.L., & Zhang, G. (2014). Improved performance of partly pit exhaust systems in pig housing. https://doi.org/10.13031/AIM.20141899147

Rong, L. (2020). Effect of partial pit exhaust ventilation system on ammonia removal ratio and mass transfer coefficients from different emission sources in pig houses. https://doi.org/10.1016/J.ENBENV.2020.04.006

Jacobson, L.D., Hetchler, B.P., & Schmidt, D.R. (2007). Sampling pit and wall emission for H2S, NH3, CO2, PM, & odor from deep-pit pig finishing facilities. https://doi.org/10.13031/2013.23886

Arogo, J., Zhang, R., Riskowski, G., & Christianson, L. (n.d.). Mass Transfer Coe $ cient of Ammonia in Liquid Swine Manure and Aqueous Solutions.

Barker, J., Curtis, S., Hogsett, O., & Humenik, F. (n.d.). Safety in swine production systems.

Arogo, J. (n.d.). Hydrogen sulfide emission and control parameters from stored liquid swine manure.

Patni, N.K., & Clarke, S.P. (2003). Gaseous Emissions in Swine Barns and During Slurry Mixing in Sub-Floor Pits. https://doi.org/10.13031/2013.14099

Choi, Y., Ha, D., Lee, S., & Kim, D. (2022). Effect of aerobically treated manure on odorous material emissions from a swine finishing barn equipped with a continuous pit recirculation system. https://doi.org/10.5713/ab.21.0135

Zhang, G., & Zong, C. (2014). An engineering approach for effective cleaning exhaust air from livestock housing - A Review of Danish experiences of using partial pit air exhaust.

Park, J.H., Park, J.H., Peters, T.M., Altmaier, R., Jones, S., Gassman, R., & Anthony, T.R. (2017). Simulation of Air Quality and Operating Cost to Ventilate Swine Farrowing Facilities in the Midwest U.S. During Winter. https://doi.org/10.13031/TRANS.11784

Rong, L., & Wang, X. (2023). Smart ventilation in confined animal buildings. https://doi.org/10.1007/978-3-031-24861-0_150

Hoff, S.J., Bundy, D.S., Nelson, M.A., Zelle, B.C., Jacobson, L.D., Heber, A.J., Ni, J., Zhang, Y., Koziel, J.A., & Beasley, D.B. (2006). Emissions of ammonia, hydrogen sulfide, and odor before, during, and after slurry removal from a deep-pit swine finisher.. https://doi.org/10.1080/10473289.2006.10464472

Predicala, B.Z., Maghirang, R.G., Jerez, S.B., Urban, J.E., & Goodband, R.D. (2000). Air quality in swine-finishing barns.. https://doi.org/10.4148/2378-5977.6583

Barker, J., Curtis, S., Hogsett, O., & Humenik, F. (n.d.). Safety in swine production systems.

Muhlbauer, R., Swestka, R.J., Burns, R.T., Xin, H., Hoff, S.J., & Li, H. (2008). Development and testing of a hydrogen sulfide detection system for use in swine housing. https://doi.org/10.13031/2013.25089

Patni, N.K., & Clarke, S.P. (2003). Gaseous Emissions in Swine Barns and During Slurry Mixing in Sub-Floor Pits. https://doi.org/10.13031/2013.14099

REFERENCES

Arogo, J., Zhang, R., Riskowski, G., & Christianson, L. (n.d.). Mass Transfer Coe $ cient of Ammonia in Liquid Swine Manure and Aqueous Solutions.

Janni, K.A., Jacobson, L.D., & Hetchler, B.P. (2008). Three-zone model of ammonia and hydrogen sulfide in a deep-pit swine finishing barn.. https://doi.org/10.13031/2013.25503

Seok, J. (n.d.). Assessment of Hydrogen Sulfide and Ammonia Concentrations in Swine, Poultry, Cattle Farms.

Reeve, K.A., Peters, T.M., & Anthony, T.R. (2013). Wintertime factors affecting contaminant distribution in a swine farrowing room.. https://doi.org/10.1080/15459624.2013.777303

Wilhelm, L.R., & McKinney, D.B. (2001). Environmental measurements in production swine facilities. https://doi.org/10.13031/2013.6913

Barker, J., Curtis, S., Hogsett, O., & Humenik, F. (n.d.). Safety in swine production systems.

Choi, Y., Ha, D., Lee, S., & Kim, D. (2022). Effect of aerobically treated manure on odorous material emissions from a swine finishing barn equipped with a continuous pit recirculation system. https://doi.org/10.5713/ab.21.0135

Predicala, B.Z., & Alvarado, A.C. (2013). Assessment of occupational exposure risk of workers to dust, gases and noise in swine grow-finish facilities. https://doi.org/10.13031/AIM.20131620731

Charavaryamath, C., & Singh, B. (2006). Pulmonary effects of exposure to pig barn air.. https://doi.org/10.1186/1745-6673-1-10

Predicala, B.Z., & Alvarado, A.C. (2013). Assessment of occupational exposure risk of workers to dust, gases and noise in swine grow-finish facilities. https://doi.org/10.13031/AIM.20131620731

Peters, T.M., Anthony, T.R., Taylor, C., Altmaier, R., Anderson, K., & O'Shaughnessy, P.T. (2012). Distribution of Particle and Gas Concentrations in Swine Gestation Confined Animal Feeding Operations. https://doi.org/10.1093/ANNHYG/MES050

Charavaryamath, C., Janardhan, K.S., Townsend, H.G., Willson, P., & Singh, B. (2005). Multiple exposures to swine barn air induce lung inflammation and airway hyper-responsiveness.. https://doi.org/10.1186/1465-9921-6-50

Barker, J., Curtis, S., Hogsett, O., & Humenik, F. (n.d.). Safety in swine production systems.

Hoff, S.J., Bundy, D.S., Nelson, M.A., Zelle, B.C., Jacobson, L.D., Heber, A.J., Ni, J., Zhang, Y., Koziel, J.A., & Beasley, D.B. (2006). Emissions of ammonia, hydrogen sulfide, and odor before, during, and after slurry removal from a deep-pit swine finisher.. https://doi.org/10.1080/10473289.2006.10464472

Charavaryamath, C., Janardhan, K.S., Townsend, H.G., Willson, P., & Singh, B. (2005). Multiple exposures to swine barn air induce lung inflammation and airway hyper-responsiveness.. https://doi.org/10.1186/1465-9921-6-50