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Development and field evaluation of a hybrid FOPBIACA system for ammonia and hydrogen sulfide removal from swine farm emissions

Phimphaka Phothilangka[1]

[1] Department of Environmental Science and Technology, Faculty of Science, Lampang Rajabhat University, Muang, Lampang 52100, Thailand
E-mail: phimphaka@g.lpru.ac.th

ABSTRACT

Odor emissions from swine farms, particularly ammonia (NH_3) and hydrogen sulfide (H_2S), present significant environmental challenges. This study developed and field-evaluated a hybrid deodorization system (FOPBIACA) integrating physical, chemical, and biological processes. The system was operated at a commercial swine farm in Thailand, treating approximately 220,000 $m^3 h^{-1}$ of exhaust air over a 5-month production cycle. The system includes particulate filtration, biological filtration, chemical scrubbing, iron-based filtration, and charcoal adsorption. Ammonia concentrations were reduced from 22–84 ppm to 0–10 ppm, with removal efficiencies reaching up to 100%. Hydrogen sulfide concentrations were effectively maintained well below the 10 ppm safety threshold. Intermediate measurements suggested that the combined pre-treatment and biological filtration stages accounted for most of the pollutant removal, while the chemical and adsorption stages significantly improved performance under elevated loading conditions. Operational results indicated that the system can be flexibly controlled based on real-time pollutant loads, allowing for reduced energy consumption during low-load periods. Throughout the study, no significant clogging was observed, and odor nuisance was substantially mitigated. The FOPBIACA system demonstrates strong potential as a practical, scalable, and operationally resilient solution for comprehensive odor control in intensive livestock production.

Keywords: ammonia, biofiltration, hydrogen sulfide, odor control, swine farm.

INTRODUCTION

Odor emissions from intensive livestock production, particularly swine farming, have become a significant environmental and social concern worldwide. Among the odorous compounds emitted from swine production systems, ammonia (NH_3) and hydrogen sulfide (H_2S) are considered major contributors to odor pollution due to their strong odor intensity, environmental impacts, and toxic effects at elevated concentrations (Wang et al., 2021; Ren et al., 2025). Elevated concentrations of these gases pose health risks to farm workers and adversely affect surrounding communities, often resulting in odor complaints and conflicts (Akdeniz and Janni, 2012; Liu et al., 2014). Therefore, effective odor management strategies are essential for sustainable livestock production.

Various technologies have been developed to mitigate odor emissions from swine farms (Halder and Lee, 2020), including dietary modification (Dinh et al., 2022; Kim et al., 2025), chemical treatment (Dai and Blanes-Vidal, 2013; Sheng et al., 2015), biofiltration (Kafle et al., 2015; Febrisiantosa et al., 2020), and advanced oxidation processes (Lee et al., 2021; Han et al., 2024; Maurer and Koziel, 2019). Among these, biofiltration has been widely recognized as an environmentally friendly and cost-effective approach for ammonia removal, with reported removal efficiencies commonly exceeding 90% under optimized operating conditions (Barbusinski et al., 2017; Liu et al., 2014; Wu et al., 2018). However, conventional single-stage biofilters often face limitations such as sensitivity to environmental conditions, clogging due to particulate accumulation, and reduced efficiency under fluctuating pollutant loads (Akdeniz and Janni, 2012). Similarly, chemical and physical treatment methods, while effective in certain applications, may be constrained by operational costs, secondary pollution, or limited adaptability (Liu et al., 2014).

To address these limitations, recent research has focused on the development of hybrid treatment systems that integrate physical, chemical, and biological processes. Such systems can enhance overall performance by combining the advantages of individual treatment methods while minimizing their drawbacks. Multi-stage configurations have been shown to improve pollutant removal efficiency, operational stability, and adaptability under variable loading conditions (Estrada et al., 2011; Torretta et al., 2013).

Despite these advancements, there remains a lack of field-scale evaluations of integrated deodorization systems under actual swine farming conditions. Many existing studies have been conducted at laboratory or pilot scales, which may not fully represent the complexity of real-world operations. Furthermore, limited attention has been given to adaptive operational strategies that optimize system performance while reducing energy consumption and maintenance requirements.

In this context, the present study aims to develop and evaluate a novel hybrid deodorization system, namely FOPBIACA, designed to treat odor emissions from swine farms using a combination of physical filtration, biological treatment, and chemical processes within a single integrated unit. The system was implemented and tested in a commercial swine farm under field conditions.

The specific objectives of this study were to:

1. evaluate the removal efficiency of NH_3 and H_2S using the FOPBIACA system;
2. assess the operational performance and practical applicability of the system under real farm conditions; and
3. compare the effectiveness of the system with existing deodorization technologies.

MATERIALS AND METHODS

Design and configuration of the FOPBIACA system

The FOPBIACA deodorization system was developed as an integrated air treatment unit combining physical, chemical, and biological processes within a single structure. The system was configured as a closed tunnel-type chamber (12 × 7 × 1.8 m) constructed from brick and cement, designed to force odor-laden air emitted from a swine housing facility to pass sequentially through multiple treatment layers before discharge into the atmosphere.

The airflow was maintained at an average velocity of 2 m s^{-1}, corresponding to an air contact (residence) time of approximately 2.23 s within the system. The treatment unit was designed to treat approximately 220,000 m^3 h^{-1} of exhaust air from a mechanically ventilated closed-house swine finishing facility housing approximately 700 swine per production cycle. Performance evaluation was conducted during the late finishing phase (4–5 months of age), a period typically characterized by peak odor emission and ventilation loading as a result of increased animal biomass and manure accumulation.

The overall configuration and operational sequence of the FOPBIACA system are illustrated in Figure 1. The system consists of six sequential filtration/treatment layers arranged along the airflow direction:

1. Primary particulate filtration (Layer 1): Nylon mesh panels were installed perpendicular to the airflow to capture coarse dust particles. The panels were spaced at 30–50 cm intervals to prevent complete blockage and allow partial airflow bypass in case of clogging.
2. Secondary particulate filtration (Layer 2): A second set of nylon mesh filters was installed downstream at an inclination of 50–60°, arranged in a staggered (zigzag) configuration to increase surface area and enhance fine particulate capture efficiency.
3. Biological filtration (Layer 3): Coconut husks were used as the biofilter packing material because of their porous fibrous structure, high moisture-retention capacity, and suitability for microbial attachment. Prior to installation, the packing material was pre-fermented and inoculated with a commercial consortium of odor-degrading microorganisms to promote rapid biofilm establishment.

The coconut husks were loosely packed into modular trays at a bulk density of approximately 200 kg m^{-3} to minimize airflow resistance while maintaining adequate void space for gas transport. The trays were vertically arranged and inclined at 30–35° to the incoming airflow, allowing odorous air to pass uniformly through the packing material.

The moisture content of the biofilter bed was maintained at approximately 50–60%. Continuous water spraying was applied during the initial acclimation period to facilitate microbial colonization, after which the irrigation system was operated intermittently (3 min on and 10 min off) to maintain bed moisture while reducing water and energy consumption. The bed pH was maintained between 6.0 and 7.0 throughout the study.

Although temporal changes in the physicochemical properties of the packing material were not quantitatively monitored, these parameters were qualitatively observed during routine system operation.

4. Alkaline spray filtration (Layer 4): Nylon mesh panels combined with an alkaline aerosol spray (pH 8.5–9.0) were used to enhance the removal of hydrogen sulfide (H_2S) through absorption and chemical interaction.
5. Iron-based filtration (Layer 5): Steel wool or iron shavings were employed as reactive media for H_2S removal. Hydrogen sulfide reacts with iron oxide (Fe_2O_3) to form iron sulfide (Fe_2S_3), which can be regenerated upon exposure to oxygen, according to the following reactions:

$$Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O \quad (1)$$

$$2Fe_2S_3 + 3O_2 \rightarrow 2Fe_2O_3 + 6S \quad (2)$$

6. Charcoal filtration (Layer 6): A final polishing stage using charcoal filter was applied to adsorb residual odors and trace gases via microporous adsorption.

A three-component spray system was incorporated into the treatment train, comprising an upstream weak acidic spray, an intermediate water spray for biofilter moisture control, and a downstream weak alkaline spray (Figure 1).

Table 1. Constant operating parameters of the FOPBIACA system

Parameter	Value
Airflow rate	125,000–220,000 $m^3 h^{-1}$
Average air velocity	2.0 $m s^{-1}$
Average gas residence time	2.23 s
Average spray flow rate	160 $L h^{-1}$
Acidic solution pH	4.0–4.5
Alkaline solution pH	8.5–9.0
Biofilter moisture content	50–60%
Biofilter bed pH	6.0–7.0
Packing density (coconut husks)	200 $kg m^{-3}$
Average operating temperature	29 ± 1 °C

Experimental setup and operating conditions

The FOPBIACA system was installed and operated at a commercial fattening swine farm in Mae Tha District, Lampang Province, Thailand, under continuous field conditions. The system was designed to continuously treat exhaust air discharged from a mechanically ventilated swine house throughout a five-month production cycle. The principal operating conditions of the FOPBIACA system are summarized in Table 1.

The spray system consisted of three functional components. A weak acidic spray (pH 4.0–4.5) was applied at the inlet section to enhance NH_3 absorption and facilitate particulate agglomeration. Water spraying was used to maintain the moisture content of the biofilter medium at approximately 50–60%, thereby providing favorable conditions for microbial activity. A weak alkaline spray (pH 8.5–9.0) was installed downstream of the biological filter to enhance H_2S removal through chemical absorption.

To accommodate changes in pollutant loading during the swine production cycle, the system was operated under two operational regimes, as summarized in Table 2. During the early fattening stage (swine aged 2–3 months), odor emissions remained relatively low and only partial system operation was required. As the swine approached market weight (swine aged 3–5 months), pollutant loading increased substantially, and the operating schedule was adjusted accordingly by increasing ventilation capacity and extending the operating periods of the acidic and alkaline spray systems.

Routine maintenance was conducted throughout the experiment to ensure stable system performance. Maintenance activities included periodic cleaning of the nylon pre-filters to prevent particulate accumulation, regular inspection of spray nozzles and pumps, and replacement of the charcoal when adsorption performance declined.

Measurement of purification efficiency

The deodorization performance of the FOPBIACA system was evaluated based on the removal efficiency of key odorous compounds, ammonia (NH_3) and hydrogen sulfide (H_2S). Air samples were collected at two main sampling

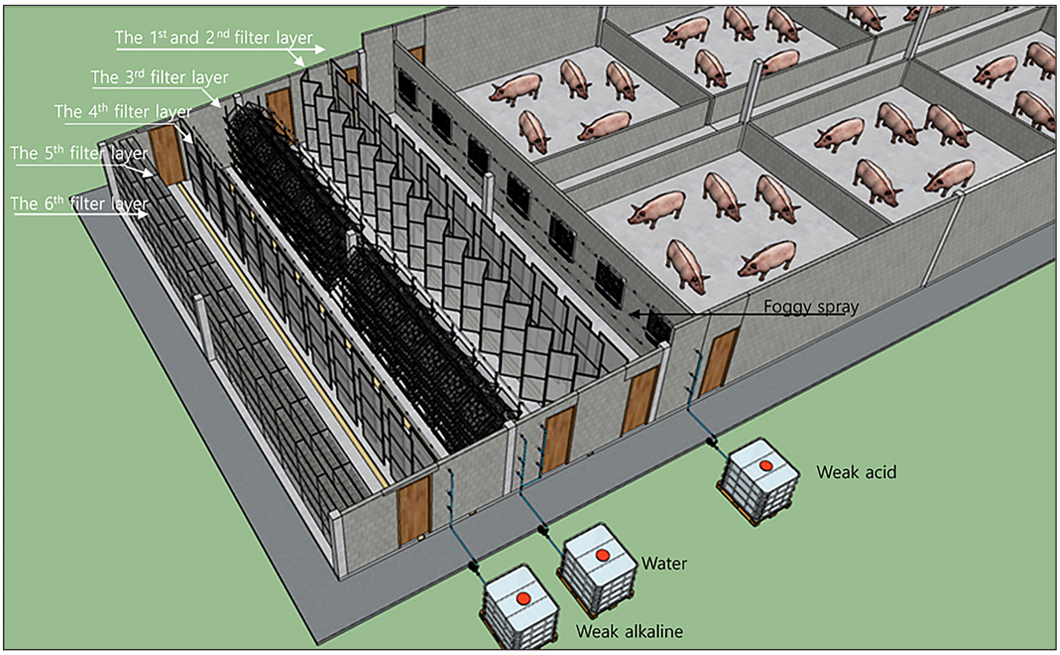

Figure 1. Schematic diagram of the FOPBIACA system showing the six sequential filtration and treatment layers along the airflow direction

Table 2. Operational conditions of the FOPBIACA system during the swine production cycle

Parameter	Phase I : Early fattening (Swine aged 2–3 months)	Phase II : Late fattening (Swine aged 3–5 months)
Pollutant loading	Low	High
Ventilation fans	4 of 7 fans	7 of 7 fans
Acidic spray (pH 4.0–4.5)	2 h morning + 2 h evening	5 h early morning + 5 h evening
Water spray	3 min on / 10 min off	3 min on / 10 min off
Alkaline spray (pH 8.5–9.0)	Not operated	5 h early morning + 5 h evening
Purpose of operation	Moisture control and NH_3 mitigation under low odor loading	Enhanced NH_3 and H_2S control under elevated odor loading

points: (i) upstream of the treatment system (immediately behind the swine house exhaust fans) representing untreated air, and (ii) downstream of the system representing treated air after passing through all filtration stages.

The purification efficiency was expressed as the percentage reduction in pollutant concentration before and after treatment. The deodorization efficiency was calculated according to the following equation (Barbusinski et al., 2017; Liu et al., 2017):

$$\textit{Deodorization efficiency} = \frac{C_i - C_o}{C_i} \times 100 \quad (3)$$

where: C_i – inlet concentration (before treatment), C_o – outlet concentration (after treatment).

All measurements were conducted under normal operating conditions of the swine farm to reflect real-field performance of the system.

Analytical methods

The concentrations of ammonia and hydrogen sulfide in the airstream were measured using a portable gas analyzer (Bio Genius, Model IRCD4 210406). To ensure measurement accuracy, selected air samples were simultaneously collected and analyzed using a gas chromatograph (Agilent Technologies, Model 7890A), which served as a reference method for calibration and validation of the portable instrument.

The experimental design followed a completely randomized design (CRD) with three independent replications. Concentration data obtained from inlet and outlet sampling points were used to evaluate treatment performance.

Statistical analysis was performed to compare mean concentrations and removal efficiencies using Duncan's new multiple range test (DMRT) at a 95% confidence level ($p < 0.05$). Differences between inlet and outlet concentrations of NH_3 and H_2S were used as indicators of system effectiveness in odor mitigation within the swine house ventilation system.

RESULTS AND DISCUSSION

The performance of ammonia and hydrogen sulfide removal

Overall deodorization

The continuous monitoring over the 8-week period during the late fattening stage of the production cycle (when the swine were approximately 3–5 months of age) demonstrated the effective performance of the integrated FOPBIACA system in mitigating ammonia (NH_3) and hydrogen sulfide (H_2S) emissions from the commercial tunnel-ventilated swine house. Post-treatment concentrations remained consistently low throughout the monitoring period, with NH_3 concentrations ranging from 0 to 10 ppm and H_2S from 0 to 6 ppm. The system achieved maximum removal efficiencies approaching 100% for both gases during multiple weeks (Table 3). These findings demonstrate the effectiveness of the integrated treatment process, in which physical filtration, chemical scrubbing (acidic and alkaline sprays), biological filtration, iron-based oxidation, and charcoal adsorption collectively contributed within a total gas residence time of only 2.23 s.

Influence of real-field inlet fluctuations

Despite the high treatment efficacy, the pretreatment (inlet) concentrations exhibited significant temporal variations, with NH_3 fluctuating between 22 and 84 ppm, and H_2S between 6 and 39 ppm. These elevated and widely fluctuating inlet concentrations accurately reflect the dynamic inhouse conditions of a closed EVAP housing system. The exhaust fans effectively draw and accumulate heat, moisture, and volatilized gases along the 12-meter length of the building, resulting in peak concentrations at the exhaust end (Banhazi, 2013; Costantino et al., 2016).

A critical peak was observed during Week 6, where inlet concentrations surged significantly (NH_3: up to 84 ppm; H_2S: up to 39 ppm). As the experiment was conducted during the late finishing phase (4–5 months of age), this peak likely corresponds to the maximum animal biomass period, resulting in massive manure and urine excretion. Consequently, the rapid volatilization of NH_3 and the anaerobic degradation of sulfate-containing compounds leading to H_2S generation in the manure pit were at their highest (Philippe et al., 2011).

System resilience and shock load responses

The extreme pollutant load in Week 6 provided crucial insights into the FOPBIACA system's resilience under shock load conditions. During this peak period, the minimum removal efficiencies experienced a transient decline, dropping to 64.3% for NH_3 and 40.0% for H_2S. This reduction indicates a momentary saturation point within the sequential treatment layers, a phenomenon

Table 3. Results of ammonia and hydrogen sulfide measurements before and after treatment with deodorization system in swine farms

Week	NH_3			H_2S		
	Before treatment (ppm)	After treatment (ppm)	Removal efficiency (%)	Before treatment (ppm)	After treatment (ppm)	Removal efficiency (%)
1	22–57	0–5	77.3–100.0	10–31	0–1	90.0–100.0
2	22–55	0–4	81.8–100.0	12–29	0.3–2	83.3–99.0
3	22–64	0–5	77.3–100.0	14–32	0.2–3	78.6–99.4
4	23–60	0–5	78.3–100.0	12–30	0.2–2	83.3–99.3
5	24–66	1–5	79.2–98.5	6–28	0–2	66.7–100.0
6	28–84	2–10	64.3–97.6	10–39	1–6	40.0–97.4
7	26–54	1–6	76.9–98.1	12–36	1–5	58.3–97.2
8	25–50	0–5	80.0–100.0	10–32	0.4–2	80.0–98.8

frequently observed in biofiltration and chemical scrubbing systems when subjected to sudden pollutant surges (Rybarczyk et al., 2019).

For NH_3, the rapid surge likely challenged the absorption capacity of the weak acidic spray (pH 4.0–4.5) at the inlet zone and the subsequent biofilter layer. For H_2S, the intense concentration may have briefly exceeded the stoichiometric reaction limits of the iron-based filtration layer ($Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O$) and the alkaline spray (pH 8.5–9.0). However, the system's ability to maintain maximum efficiencies of 97.6% and 97.4% for NH_3 and H_2S, respectively, even during this peak week, underscores the robustness of the multi-layer design. The final polishing stage (charcoal) played a vital role in capturing the residual gases that bypassed the upstream biological and chemical layers.

Implications for animal welfare

While the FOPBIACA system successfully operates as an end-of-pipe solution to mitigate external emissions (220,000 $m^3\ h^{-1}$), the highly concentrated pre-treatment air measured directly behind the exhaust fans raises significant in-house animal welfare concerns. The measured inlet air concentrations frequently exceeded the recommended safety thresholds for optimal swine health and productivity, where NH_3 is advised to be maintained well below 25 ppm, and ideally below 7–10 ppm (Michiels et al., 2015; Donham, 1991). Prolonged exposure to such elevated levels in the downwind sections of the barn can induce respiratory stress, mucosal irritation, and significantly increase the prevalence of lung lesions and pleurisy in finishing pigs (Michiels et al., 2015). This highlights that while the FOPBIACA system effectively protects the surrounding environment, supplementary in-house strategies, such as increasing ventilation rates or optimizing manure pit clearing frequency, are essential to dilute internal gas accumulations.

Contribution of the integrated treatment train

The first and second treatment layers primarily functioned as physical pre-treatment units designed to intercept particulate matter from the incoming air stream. Although quantitative dust removal efficiency was not analytically measured in this study, routine visual inspections consistently revealed a substantial and dense accumulation of captured dust on the nylon mesh panels of these initial layers. While these early stages contributed minimally to the direct removal of gaseous pollutants, their observed capacity to capture bulk particulates was considered critical. This physical interception effectively prevented the downstream biological and adsorption media from premature clogging, thereby minimizing pressure drop accumulation and ensuring the operational stability of the overall treatment process.

Although comprehensive gas characterization was not performed at every treatment stage, intermediate measurements obtained immediately downstream of the biological filtration unit (Layer 3) provided insight into the contribution of the upstream treatment processes. At this location, NH_3 concentrations ranged from 1 to 11 ppm, representing a substantial reduction from the inlet concentrations of 22–84 ppm. Similarly, H_2S concentrations decreased from 6–39 ppm at the system inlet to 0.3–8.0 ppm after the biological filtration stage. These intermediate results suggest that the combined action of the acidic spray (pH 4.0–4.5), the physical filtration units (Layers 1 and 2), and the biological filtration process substantially reduced the concentrations of both NH_3 and H_2S before the exhaust air entered the subsequent polishing stages.

Intermediate measurements suggest that most pollutant removal occurred within the combined pre-treatment and biological filtration stages prior to the downstream polishing units. This observation is consistent with previous studies demonstrating that biological filtration is an effective process for removing NH_3 and other biodegradable odorous compounds from livestock exhaust air (Liu et al., 2017; Cabrol et al., 2012). Nevertheless, the downstream adsorption and chemical treatment units likely contributed to the stable operation of the integrated treatment system by providing additional polishing capacity, particularly under fluctuating pollutant loading conditions. The consistently low outlet concentrations of NH_3 and H_2S throughout the monitoring period indicate that the sequential combination of physical, biological, chemical, and adsorption processes provided reliable odor mitigation under practical field conditions.

In summary, the FOPBIACA system functions as an integrated hybrid treatment system in which physical separation, biological degradation, chemical treatment, and adsorption processes operate sequentially to achieve effective odor mitigation. Intermediate measurements indicate that most pollutant removal occurred within the combined pre-treatment and biological filtration stages, while the downstream polishing units likely contributed to maintaining consistently low outlet concentrations under variable pollutant loading conditions. Collectively, these treatment processes provided reliable NH_3 and H_2S removal and supported stable long-term operation under practical commercial farm conditions.

Comparison with existing deodorization technologies

The comparative analysis presented in Table 4 indicates that the FOPBIACA system provides odor mitigation performance that is comparable to, and in some cases exceeds, several established livestock deodorization technologies. In particular, the NH_3 removal performance achieved in the present study (64.3–100%, with maximum efficiencies approaching complete removal) was substantially higher than that typically reported for source-control strategies, such as diet modification (11–63%) (Sajeev et al., 2018; Dinh et al., 2022) and generally comparable to or higher than permeable cover systems (30–90%) (Liu et al., 2014). Simultaneously, the system's performance remains well within the optimal range reported for advanced biological treatment technologies, including conventional biofilters and microbial deodorization systems (70–95%) (Kafle et al., 2015; Wu et al., 2018).

The competitive NH_3 mitigation performance of the FOPBIACA system, relative to source-control approaches, may be attributed to its direct treatment of exhaust air rather than the indirect reduction of odor precursors. Although dietary manipulation can effectively decrease nitrogen excretion, its overall effectiveness is often influenced by animal physiology, feed composition, and farm management practices. In contrast, the FOPBIACA system directly treats emitted exhaust air, making its performance less dependent on variations in production conditions and enabling consistently high NH_3 removal under field conditions. Furthermore, compared with standalone biological deodorization technologies, the FOPBIACA system achieved comparable NH_3 removal efficiencies despite operating under dynamic commercial farm conditions. These findings suggest that integrating physical, biological, and chemical treatment processes within a single treatment train can enhance overall deodorization performance while maintaining stable operation under practical field conditions.

Nevertheless, while the H_2S removal efficiency of the FOPBIACA system reached up to 100% under normal conditions, it experienced transient

Table 4. Comparative performance of existing deodorization technologies for livestock odor mitigation

Technology	Description	Effectiveness	Citation
FOPBIACA	An integrated system combining physical, biological, and chemical processes to eliminate unpleasant odors from livestock facilities.	Reduces NH_3 emissions by 64–100% and H_2S emissions by 40–100%.	This study
Diet modification	Alteration of animal feed composition to minimize the excretion of odor-causing precursors.	Reduces NH_3 emissions by 11–63%.	Sajeev et al. (2018); Wang et al. (2022)
Permeable covers	Geotextile fabric-straw covers applied to manure storage to form a physical barrier and promote biological degradation.	Reduces overall odor by 40–90% and NH_3 emissions by 30–90%.	Liu et al. (2014)
Biofilters	Systems utilizing microorganisms immobilized on packed media to biologically oxidize NH_3 and other odorous compounds.	Reduces NH_3 by 70–95% and significantly lowers H_2S emissions.	Kafle et al. (2015); Liu et al. (2017)
Chemical treatment	Application of acidic or oxidizing solutions to capture gaseous pollutants, converting NH_3 into non-volatile salts and suppressing H_2S.	Reduces NH_3 emissions by 70–96% and odor/H_2S by 30–70%.	Liu et al. (2014); Barbusinski et al. (2017)
Slurry acidification	Utilization of sulfuric acid to lower manure pH, shifting the ammonium-ammonia equilibrium toward the non-volatile ammonium form.	Reduces NH_3 emissions by 50–70% under practical field conditions.	Dai and Blanes-Vidal (2013); Overmeyer et al. (2023)
Photocatalytic oxidation	Systems employing UV-activated catalysts (e.g., TiO_2) to generate reactive radicals for the oxidation of NH_3, H_2S, and VOCs.	Reduces NH_3 by 80–98%, H_2S by 80–90%, and overall odor by 70–99%.	Lee et al. (2021); Han et al. (2024)
Microbial deodorization	Inoculation of beneficial microorganisms to biologically degrade NH_3, H_2S, and other odorants in exhaust air.	Reduces NH_3 and H_2S emissions by 80–95% and overall odor by 70–90%.	Wu et al. (2018); Rybarczyk et al. (2019)

declines (down to 40%) during peak loading periods. This temporary reduction in minimum efficiency is relatively lower than the highly stable values (exceeding 80%) commonly reported for specialized biological systems and advanced oxidation technologies operated under optimized or laboratory-controlled conditions (Han et al., 2024; Kafle et al., 2015; Lee et al., 2021). The fluctuations in H_2S reduction observed in the FOPBIACA system under shock loads may reflect transient saturation of the chemical and biological layers, insufficient gas residence time during extreme concentration surges, or sub-optimal microbial community composition for rapid sulfur oxidation. Importantly, however, despite these transient drops in percentage efficiency, the absolute concentration of treated H_2S remained strictly below the recommended occupational exposure threshold of 10 ppm established by NIOSH (2024) at all times, indicating that the system successfully achieved regulatory compliance under the tested field conditions. This finding implies that, although further optimization of sulfur removal kinetics under extreme loads is desirable, the current FOPBIACA configuration provides effective and safe odor control for practical livestock applications.

While chemical scrubbers and slurry acidification technologies can also achieve substantial NH_3 reductions, their implementation typically necessitates continuous chemical inputs, raising significant concerns regarding elevated operational costs, equipment corrosion, and occupational handling safety (Overmeyer et al., 2023). In contrast, the FOPBIACA system offers a highly integrated treatment approach that minimizes reliance on intensive chemical dosing while sustaining exceptional NH_3 removal performance. This specific characteristic greatly enhances its practical applicability, economic feasibility, and long-term environmental sustainability in commercial swine operations.

Overall, the comparative assessment demonstrates that the FOPBIACA system performs competitively alongside currently available deodorization technologies, particularly regarding NH_3 mitigation. While targeted modifications are required to optimize H_2S removal, the strategic combination of physical, biological, and chemical treatment processes provides a highly promising and robust framework for comprehensive odor management in intensive livestock production. Future research should focus on evaluating the system's long-term operational stability, characterizing its performance under seasonal environmental variations, and quantifying the removal efficiency of other critical trace odorants, including VOCs, to conclusively validate the technology's scalability for commercial deployment.

Operational performance and practical

The staged operational strategy of the FOPBIACA system enabled treatment intensity to be adjusted according to pollutant loading during different phases of the swine fattening cycle. This adaptive operation significantly optimized resource utilization while maintaining effective deodorization performance. The total electrical energy consumption was calculated based on the horsepower of the operating pumps and their corresponding operating durations. Under a conventional continuous full-capacity operation (24 h day^{-1}), the system would require an estimated 7520 kWh per production cycle. In contrast, the staged operational strategy reduced the actual electrical energy consumption to 4780 kWh, representing an energy saving of approximately 36.4%. These savings were primarily achieved through reduced pump operation and optimized chemical dosing, thereby lowering operating costs and improving the overall sustainability of the treatment system.

Throughout the experimental period, no significant clogging, media compaction, excessive pressure drop, or airflow obstruction was observed during routine operation, indicating that the selected packing configuration maintained stable airflow distribution and reliable treatment performance under practical field conditions. The preliminary particulate filtration stages likely contributed to this operational stability by reducing particulate accumulation within the downstream biological and adsorption media.

Community feedback collected during the monitoring period indicated a high level of social acceptance, with no odor complaints reported by nearby residents. Although odor perception is inherently subjective, the absence of complaints provides supportive qualitative evidence that the integrated treatment system effectively mitigated odor nuisance under practical operating conditions, complementing the measured reductions in NH_3 and H_2S concentrations.

Overall, the findings demonstrate that the FOPBIACA system combines operational flexibility, stable treatment performance, and reduced energy consumption, making it a promising and practical odor mitigation technology for commercial tunnel-ventilated swine production facilities. The ability to adjust treatment intensity according to pollutant loading further enhances its long-term applicability by reducing unnecessary chemical and energy consumption while maintaining effective odor control under dynamic field conditions.

Limitations and future perspectives

Despite the highly promising performance demonstrated by the FOPBIACA system under field conditions, several limitations of the current study must be acknowledged. First, the experimental evaluation was conducted over a single swine production cycle (approximately five months). Consequently, the long-term operational stability of the system, particularly concerning the physical durability of the filtration media, the succession dynamics of the microbial community, and the gradual accumulation of pressure drop, was not comprehensively evaluated. These temporal factors are critical, as they can significantly influence sustained treatment efficiency and dictate the maintenance requirements during prolonged, multi-cycle operations.

Second, an in-depth economic feasibility assessment was beyond the scope of this study. To fully evaluate the practical scalability of the FOPBIACA system for commercial livestock operations, future research must incorporate a comprehensive life-cycle cost analysis (LCCA). This should meticulously account for energy consumption, chemical usage, frequency of media replacement, labor requirements, and routine maintenance costs.

Furthermore, environmental parameters such as ambient temperature, relative humidity, and seasonal variability inevitably influence biological reaction kinetics and overall pollutant removal performance. Because this study was bound by specific climatic conditions, subsequent investigations conducted across different seasons and varying livestock production scales are strongly recommended. Such studies are necessary to validate the systemic adaptability and robustness of the multi-stage configuration in diverse geographical and operational settings.

Looking forward, future research should also focus on process optimization. Investigating novel or modified media compositions, enhancing internal airflow distribution to prevent channeling, mapping the biofilter's microbial community structure via molecular techniques, and integrating automated, sensor-driven operational control strategies (e.g., automated dosing and staging) will be pivotal. Such advancements will not only further improve treatment efficiency and long-term reliability but also facilitate the broader commercial implementation of hybrid multi-stage deodorization technologies for sustainable livestock odor management.

CONCLUSIONS

This study demonstrated the effectiveness of the FOPBIACA system as a hybrid multi-stage deodorization technology for controlling odorous emissions from swine farming operations under real field conditions. The system successfully integrated physical, biological, chemical, and adsorption-based treatment processes to achieve stable and efficient removal of major odor-causing pollutants throughout the production cycle.

The system rapidly reduced odor intensity after start-up, indicating effective treatment performance and rapid stabilization under field operating conditions. Ammonia concentrations were consistently reduced from highly fluctuating inlet levels of 22–84 ppm down to 0–10 ppm, achieving removal efficiencies approaching 100%. In addition, hydrogen sulfide concentrations were effectively controlled between 0–6 ppm – remaining strictly below the 10 ppm safety threshold – despite severe fluctuations in inlet loading conditions (6–39 ppm). The H_2S removal efficiency also reached up to 100%, demonstrating the operational robustness of the system under dynamic farm environments.

Intermediate measurements indicated that substantial pollutant removal occurred before the downstream polishing stages, suggesting an important contribution from the combined pre-treatment and biological filtration processes.

Compared with existing deodorization technologies, the FOPBIACA system demonstrated competitive treatment performance while maintaining advantages in operational flexibility, low-energy operation, and practical applicability for farm-scale implementation. The modular design additionally enabled adaptive operation according to pollutant loading conditions, thereby reducing unnecessary energy consumption and operational costs. Furthermore, no major clogging issues or odor complaints were reported during the study period, supporting the practical feasibility and community acceptability of the system.

Overall, the findings suggest that the FOPBIACA system represents a promising and sustainable approach for livestock odor management. The integration of physical, biological, and chemical treatment processes provided effective pollutant removal while supporting stable operation under practical field conditions. Future studies focusing on long-term operational stability, economic analysis, and optimization under diverse environmental conditions will further support the large-scale implementation and commercialization of hybrid deodorization systems in sustainable livestock production.

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