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Field Applicability of an Integrated Microbial-Chemical System for Odor Reduction in Wastewater Treatment

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Abstract

Purpose: This study examined the technical basis and field applicability of an integrated microbial-chemical system for odor reduction in wastewater treatment. It focused on the functional roles of microbial agents, chemical assistance, and smart operational control in mitigating odor-generating conditions associated with wastewater and sludge handling. **Research Design & Data:** The study adopted a qualitative and technical analytical approach rather than a controlled experimental design. The analysis was based on project technical overview materials, product characterization data for BCP80 and STIMULUS, case-history documents including dosing schedules and field trends of H_2S and NH_4, and general scientific knowledge regarding odor formation, microbial degradation, urease inhibition, and process control. **Research Results:** The findings suggest that BCP80 primarily functions as a Bacillus-dominant microbial agent that may support organic matter degradation and process stabilization, whereas STIMULUS provides complementary chemical support through concentration-dependent urease inhibitory activity. Field-related materials also showed an overall decreasing trend in H_2S and NH_4 during the treatment period, indicating possible practical relevance under site conditions. However, these findings were not supported by controlled replication or statistical validation. **Conclusion:** The proposed integrated microbial-chemical system appears to be a technically plausible and potentially field-applicable approach for odor reduction in wastewater treatment. Nevertheless, its efficacy should be confirmed through future pilot-scale or full-scale studies with controlled experimental validation.

Keywords : Wastewater Treatment, Odor Reduction, Integrated Microbial-Chemical System, Bacillus Spp., Urease Inhibition.

JEL Classification Code : Q53, Q52, Q25, Q55, O33

1. Introduction

Wastewater treatment systems play a critical role in protecting public health and preserving aquatic environments (Lebrero et al., 2011). However, wastewater collection, storage, and treatment processes are often accompanied by operational problems associated with odor generation. In particular, malodorous compounds such as hydrogen sulfide (H_2S), ammonia (NH_3), methyl mercaptan, and trimethylamine are frequently generated in wastewater and sludge handling facilities, causing odor complaints, deterioration of working conditions, corrosion of treatment infrastructure, and increased maintenance costs (Talaiekhozani et al., 2016).

In practice, odor management in wastewater treatment facilities has commonly relied on chemical dosing, manual control, and operator experience (Jeon et al., 2009). Although such approaches may provide temporary relief, they are often limited by inconsistent performance, insufficient responsiveness to fluctuating process conditions, and inefficient use of treatment agents. Because odor generation is strongly influenced by dynamic variations in influent characteristics, retention conditions, and biological activity, treatment sites require more adaptive and integrated operational strategies than those provided by conventional empirical control (Czarnota et al., 2023).

Among the alternatives currently being explored, integrated microbial-chemical treatment approaches have attracted attention as potentially useful options for odor control in wastewater treatment systems. These approaches are based on the premise that mixed microbial formulations can support organic matter degradation and process stabilization, while chemical additives can provide complementary functions for suppressing odor-related reactions (Zhang et al., 2023; Moretti et al., 2024). When combined with monitoring and automated dosing systems, such integrated approaches may offer a more practical framework for field application under variable operating conditions.

The technical basis of this approach can be discussed from three perspectives. First, microbial formulations containing Bacillus spp. and related beneficial microorganisms may contribute to the decomposition of organic substrates and the stabilization of wastewater treatment conditions. Second, chemical additives with urease inhibition characteristics may help reduce ammonia-related odor generation under specific concentration ranges. Third, IoT-based monitoring and automated dosing concepts may improve operational responsiveness by enabling treatment adjustment according to real-time field conditions. Although these elements do not by themselves constitute complete proof of treatment efficacy, they provide a meaningful technical basis for evaluating the applicability of an integrated microbial-chemical system for odor reduction (Zarra et al., 2022; Prudenza et al., 2023).

Field-related materials also suggest that this approach may have practical relevance in wastewater treatment environments (Seo et al., 2022). Available technical documents, product analysis data, dosing information, and case-based trend observations indicate that integrated application of microbial and chemical agents, together with structured operation, may support odor reduction under actual site conditions. At the same time, these materials should be interpreted cautiously because they do not represent a controlled experimental dataset with statistical validation. Therefore, their value lies primarily in supporting technical interpretation and field applicability assessment rather than definitive performance verification (Sanz-Cobena et al., 2008; Silva et al., 2017).

Against this background, this study examines the technical basis and field applicability of an integrated microbial-chemical system for odor reduction in wastewater treatment. The study focuses on the functional roles of microbial and chemical components, the operational significance of monitoring and automatic dosing, and the relevance of available field-related information for practical application. By organizing existing technical materials and case-based evidence in a structured manner, this study aims to provide a practical foundation for future validation, optimization, and implementation of integrated odor reduction strategies in wastewater treatment systems.

2. Technical Basis of the Integrated Microbial-Chemical System

2.1. Odor Generation in Wastewater Treatment Systems

Odor generation is one of the most persistent operational and environmental issues in wastewater treatment systems. Malodorous compounds are produced during the collection, storage, transport, and treatment of wastewater and sludge, particularly under oxygen-limited or anaerobic conditions (Lebrero et al., 2011; Talaiekhozani et al., 2016). Among these compounds, hydrogen sulfide (H_2S) and ammonia (NH_3) are regarded as the most representative odor-causing substances, while reduced sulfur compounds and amines are also frequently reported in wastewater treatment facilities (Jeon et al., 2009; Czarnota et al., 2023). In practical wastewater treatment plants, these odorants are important not only because of their offensive smell, but also because they are closely associated with public complaints, deterioration of workplace conditions, and increased maintenance requirements (Lebrero et al., 2011; Czarnota et al., 2023).

Hydrogen sulfide is mainly formed through microbial sulfate reduction and the decomposition of sulfur-containing organic matter under anaerobic conditions (Zhang et al., 2023). Its formation is typically promoted in stagnant wastewater zones, sludge storage tanks, and other poorly aerated environments. In addition to producing a strong offensive odor, H_2S is associated with corrosion of concrete and metal structures, safety risks for workers, and increased maintenance costs (Zhang et al., 2023; Jiang et al., 2016; Austigard et al., 2018).

Similarly, ammonia is generated through the decomposition of nitrogenous organic matter and related biochemical transformations in wastewater and sludge handling processes, contributing not only to odor problems but also to broader instability in wastewater treatment operation (Dong et al., 2023; Czarnota et al., 2023). These characteristics indicate that odor control in wastewater treatment should be understood not merely as removal of emitted gases, but as management of the biochemical and environmental conditions that promote odor generation (Talaiekhozani et al., 2016; Zhang et al., 2023).

2.2. Technical Basis of the Integrated Microbial-Chemical System

Although the primary focus of this study is odor reduction, excess sludge generation and accumulation remains an important operational factor in wastewater treatment systems. Excess sludge is widely recognized as a major technical, economic, and management burden in wastewater treatment plants because it increases sludge handling, treatment, and disposal requirements and complicates plant operation (Wei et al., 2003; Wang et al., 2017; Kacprzak et al., 2017; Ferrentino et al., 2023). In practical settings, sludge production and accumulation are influenced by wastewater characteristics, biological conversion efficiency, and the stability of treatment conditions (Guo et al., 2013; Morello et al., 2022).

From a technical perspective, treatment approaches that enhance organic matter degradation, improve biomass conversion efficiency, or reduce the build-up of excess solids may contribute to sludge minimization as a secondary operational benefit (Andreottola & Foladori, 2006; Khursheed & Kazmi, 2011; Morello et al., 2022). Therefore, sludge reduction in the present study is not treated as an independently verified primary outcome, but rather as a technically relevant operational implication of the proposed integrated treatment approach.

2.3. Functional Role of Composite Microbial Agents

Microbial agents have received increasing attention in wastewater treatment because microorganisms are directly responsible for the biodegradation of organic pollutants and the stabilization of biological treatment processes (Herrero & Stuckey, 2015). In this context, composite microbial agents refer to mixed or functionally combined microbial products intended to enhance degradation capacity, improve process resilience, and support environmental control objectives such as odor reduction.

The rationale for using composite microbial agents lies in microbial diversity and functional complementarity. Different microbial groups may perform different but interrelated roles in wastewater systems. Therefore, mixed microbial products may provide broader treatment functionality than single-strain formulations (Herrero & Stuckey, 2015).

In the present study, the proposed treatment concept is based on the assumption that composite microbial agents can support organic matter degradation and improve treatment stability. In addition, by improving biodegradation efficiency, such agents may also contribute to operational benefits related to sludge minimization (Seo et al., 2022)

2.4. Functional Relevance of Bacillus and Related Microbial Groups

Among microbial candidates used in environmental applications, Bacillus species are often highlighted because of their robust survivability, enzyme-producing capability, and adaptability to variable environmental conditions. Bacillus spp. are commonly associated with the degradation of proteins, carbohydrates, lipids, and other biodegradable organic substrates. Through extracellular enzyme production, they may enhance hydrolysis and promote reduction of organic solids, thereby potentially contributing to improved wastewater treatment conditions and indirect odor control (Seo et al., 2022).

Lactic acid bacteria may also play a supportive role by affecting microbial community balance and local biochemical conditions. Their contribution to wastewater odor control is generally considered indirect, but they may influence fermentation pathways and microbial interactions (Odey et al., 2018). In addition, facultative anaerobic microorganisms are particularly valuable in wastewater environments because they can remain active under both oxygen-rich and oxygen-limited conditions, which are frequently encountered in practical treatment systems. This flexibility may improve microbial stability in real treatment facilities where redox conditions continuously fluctuate (Clements et al., 2002).

The microbial basis of the proposed treatment system can be further understood from the product characteristics of BCP80 and STIMULUS, which are summarized in Table 1.

Table 1: Product Characteristics of BCP80 and STIMULUS

Product	**Formulation**	**Bacillus count**	**Lactic acid bacteria count**	**Coliforms**	**Salmonella**	**Yeast**	**Functional note**
BCP80	Powder	5.0 × 10^9 CFU/g	2.7 × 10^9 CFU/g	N.D.	N.D.	N.D.	Microbial product dominated by *Bacillus* spp.
STIMULUS	Liquid	Detected (*Bacillus*, approx. 10^5 CFU/g)	4.1 × 10^5 CFU/g	N.D.	N.D.	N.D.	Exhibited urease inhibitor activity, especially at ≥1% concentration

Table note: The product analysis report indicates that Bacillus was detected in both products, with BCP80 containing approximately 5.0 × 10^9 CFU/g of Bacillus and 2.7 × 10^9 CFU/g of lactic acid bacteria, whereas STIMULUS contained Bacillus at approximately 10^5 CFU/g and lactic acid bacteria at 4.1 × 10^5 CFU/g. STIMULUS also exhibited urease inhibitor activity, especially at relatively high concentrations.

Table 1 shows that BCP80 and STIMULUS do not perform identical roles within the treatment system. BCP80 appears to function primarily as a microbial agent with a high abundance of Bacillus spp. and lactic acid bacteria, whereas STIMULUS appears to play a complementary biochemical role in addition to its microbial characteristics. This distinction supports the interpretation that the proposed technology is based on functional complementarity rather than on microbial addition alone.

2.5. Chemical Assistance and Odor Control Mechanisms

Although biological treatment is central to sustainable wastewater management, biological activity alone may not always be sufficient for rapid or stable odor control under field conditions. For this reason, chemical assistance is often integrated with microbial treatment. Chemical additives may suppress the generation of odor precursors, neutralize malodorous compounds, adjust local pH, or improve treatment responsiveness under transient loading conditions.

One relevant mechanism in this context is urease inhibition. Urease catalyzes the hydrolysis of urea into ammonia and carbon dioxide, and therefore inhibition of urease activity may help reduce ammonia-related odor formation (Sanz-Cobena et al., 2008). This mechanism is particularly meaningful in wastewater systems where ammonia generation contributes to odor problems and process instability. The concentration-dependent urease inhibitory activity of STIMULUS is illustrated in Figure 1.

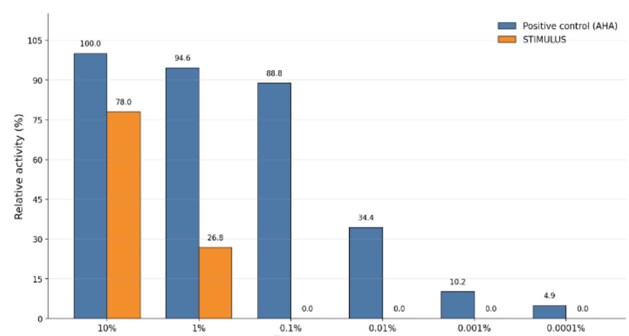

Figure 1: Relative Urease Inhibitory Activity of STIMULUS and the Positive Control (AHA) at Different Treatment Concentrations

As shown in Figure 1, STIMULUS exhibited measurable urease inhibitory activity at relatively high concentrations, whereas activity was limited at lower concentrations. This pattern suggests that the chemical contribution of STIMULUS is concentration-dependent and may be particularly relevant under conditions where active suppression of ammonia-related pathways is required. Therefore, the function of STIMULUS may be interpreted not merely as a supplementary additive, but as a component that strengthens the chemical control dimension of the integrated treatment approach.

2.6. Integrated Microbial-Chemical System and Smart Operation

Recent wastewater treatment strategies increasingly move beyond single-function treatment agents toward integrated systems combining biological treatment, chemical support, and operational automation. This shift is important because wastewater treatment conditions are highly dynamic and are often influenced by variable influent characteristics, hydraulic conditions, temperature, oxygen availability, and process disturbances.

From a technical standpoint, the effectiveness of microbial-chemical treatment is determined not only by agent composition, but also by how appropriately the treatment is applied under changing process conditions. In this regard, smart operation based on real-time monitoring and automated dosing may improve treatment efficiency by enabling adaptive control rather than fixed treatment schedules (Zarra et al., 2022). The overall structure of this integrated treatment strategy is conceptually illustrated in Figure 2.

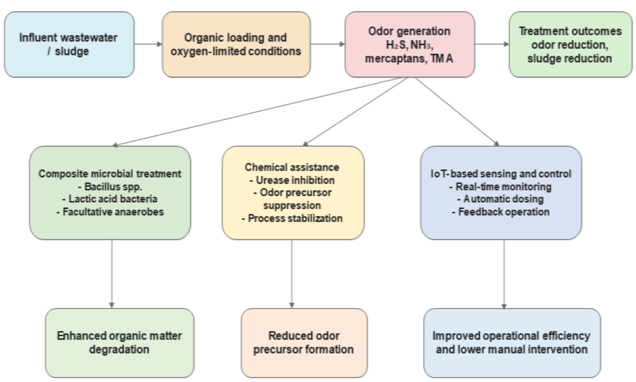

Figure 2: Integrated Microbial-Chemical Conceptual Framework for Odor Reduction in Wastewater Treatment

Figure 2 shows that the proposed technology is based on the interaction of multiple treatment elements, including microbial degradation, chemical assistance, IoT-based sensing, and automatic dosing control. Accordingly, the technology should be understood as an operational system in which biological and chemical functions are linked to monitoring and control logic. In other words, treatment performance is expected to depend not only on the intrinsic properties of the treatment agents, but also on the responsiveness and coordination of the overall operating system.

2.7. Technical Basis for Field Application

The field application of the integrated microbial-chemical system in wastewater treatment can be discussed from three perspectives: functional mechanism, operational compatibility, and site adaptability (Herrero & Stuckey, 2015). First, from the perspective of functional mechanism, the combined use of microbial and chemical components may support organic matter degradation and reduce odor precursor formation. Second, from the perspective of operational compatibility, integrated treatment may compensate for the limitations of purely biological or purely chemical approaches. Third, from the perspective of site adaptability, IoT-based monitoring and dosing control may enhance responsiveness to changing treatment conditions.

Practical implementation of this treatment concept also requires a dosing strategy that reflects field operating conditions. In this regard, the field application schedule for BCP80 and STIMULUS under the 400-ton aeration tank condition is summarized in Table 2.

Table 2: Field Dosing Schedule for BCP80 and STIMULUS under the 400-ton Aeration Tank Condition

Product	Application period	Dose per application	Total amount used	Note
STIMULUS	Days 1–3	3 kg	9 kg	Initial dosing
STIMULUS	Days 4–5	1.75 kg	3.5 kg	Reduced dosing
STIMULUS	Once weekly × 12 weeks	1.75 kg	21 kg	Maintenance dosing
STIMULUS	Total for 3 months	–	33.5 kg	Cumulative input
STIMULUS	Monthly maintenance (4 weeks)	7 kg	–	4 ppm input
BCP80	Days 1–5	4 kg	20 kg	Initial dosing
BCP80	Once weekly × 12 weeks	4 kg	48 kg	Maintenance dosing
BCP80	Total for 3 months	–	68 kg	Cumulative input
BCP80	Monthly maintenance (4 weeks)	16 kg	–	10 ppm input

Table note: The reported field dosing schedule consisted of initial *dosing followed by weekly maintenance dosing. "Total for 3 months" indicates the cumulative input over the entire 3-month application period, whereas "Monthly maintenance (4 weeks)" indicates the equivalent amount and ppm setting for the maintenance stage only. Thus, the monthly maintenance values are provided as operational reference values and are not separate from the overall 3-month dosing framework.*

3. Study Materials and Analytical Approach

3.1. Study Scope

This study was conducted to examine the technical basis and field applicability of an integrated microbial-chemical system for odor reduction in wastewater treatment. The scope of the study was defined around four major aspects: (1) odor generation characteristics in wastewater treatment processes, (2) the functional roles of microbial components, (3) the complementary significance of chemical assistance, and (4) the applicability of integrated operation supported by monitoring and automated dosing systems.

The study focused primarily on odor-causing substances such as hydrogen sulfide (H_2S) and ammonia (NH_3), which are major contributors to environmental complaints and operational difficulties in wastewater treatment facilities. Within this framework, the present study examined the technical relevance of microbial groups such as Bacillus spp., lactic acid bacteria, and facultative anaerobic microorganisms, together with chemical support mechanisms including urease inhibition. In addition, the study considered sludge minimization not as a separately verified primary outcome, but as a possible secondary operational implication of improved biodegradation and process stabilization.

The overall scope of the study was therefore not limited to a single treatment agent or a single mechanism. Rather, the study was designed to organize available technical and field-related materials into an integrated interpretation of how microbial treatment, chemical assistance, and smart operation may contribute to odor reduction under practical wastewater treatment conditions.

3.2. Study Materials

This study was based on technical and field-related materials associated with the target wastewater treatment system. The main materials used in this study included a project technical overview, product analysis data, and case-history documents related to microbial and chemical treatment agents. The project-related materials described the overall concept of an integrated microbial-chemical system for odor reduction and smart operation in wastewater treatment facilities. The product analysis materials provided information on the microbial composition of BCP80 and the urease inhibitory activity of STIMULUS. In addition, the case-history materials contained field-level information regarding dosing conditions and odor-related concentration trends during product application.

In addition to these project and field materials, the study was conceptually supported by general technical understanding of odor formation, microbial degradation, and wastewater treatment operation. However, the present study did not use a controlled experimental dataset generated specifically for this paper. Instead, it relied on structured technical interpretation of available materials related to product function, operational configuration, and field applicability.

The materials used in this study are summarized in Table 3.

Table 3: Study Materials Used in This Study

Category	Material type	Main contents	Purpose in the study
Project materials	Technical overview	Development goals, performance indicators, IoT-based operation	To define the technical background and objectives
Product analysis materials	Product characterization	Microbial composition of BCP80, urease inhibitor activity of STIMULUS	To identify functional properties of treatment agents
Case-history materials	Field application data	Dosing schedule, field trend of H_2S/NH_4, reported odor reduction	To examine practical field relevance
General scientific background	Conceptual/technical knowledge	Odor formation, sludge generation, microbial	To support theoretical interpretation

		degradation, process control	

Table note: The study was based on project-related technical documents, product analysis data, and field case materials rather than on a newly generated experimental dataset.

Table 3 indicates that the study was constructed from multiple categories of technical evidence rather than from a single document source. This is important because the study aimed to interpret the proposed system not only in terms of product composition, but also in relation to operational logic and field applicability.

3.3. Analytical Approach

The study employed a qualitative and technical analytical approach rather than an experimental verification method (Lebrero et al., 2011). First, the study reviewed the major causes and operational impacts of odor generation in wastewater treatment systems. Second, it examined the theoretical and functional basis of microbial components in relation to organic matter degradation, microbial stabilization, and indirect odor control. Third, the role of chemical assistance was analyzed with particular attention to biochemical pathways related to ammonia generation and urease inhibition. Fourth, the study considered the technical significance of integrated operation through real-time monitoring and automated dosing systems.

Based on this approach, the study attempted to organize the relationships among microbial composition, chemical support, process operation, and field applicability. Rather than presenting performance verification through controlled quantitative experiments, the study aimed to identify the technical logic and practical relevance of the integrated microbial-chemical system for odor reduction in wastewater treatment (Lebrero et al., 2011).

3.4. Analytical Perspective on Field Applicability

In this study, field applicability was discussed from the perspective of functional mechanism, operational compatibility, and site adaptability. From the viewpoint of functional mechanism, the combined use of microbial and chemical components was interpreted as a means of supporting organic matter degradation and suppressing odor-related pathways. From the viewpoint of operational compatibility, the system was considered relevant because wastewater treatment environments are dynamic and often require more adaptive control than fixed dosing or empirical operation can provide. From the viewpoint of site adaptability, the integration of sensing, monitoring, and automated dosing was regarded as a practical feature that may support treatment responsiveness under variable operating conditions (Zarra et al., 2022).

This analytical perspective is important because the proposed system was not interpreted simply as a product-based solution, but as an integrated operational approach in which biological and chemical functions are linked to monitoring and control logic. Accordingly, field applicability in the present study refers not to definitive proof of treatment efficacy, but to the practical relevance and technical plausibility of applying the proposed system in real wastewater treatment environments (Zarra et al., 2022).

3.5. Limitations of the Study

This study has several limitations. First, it was not based on a laboratory-scale or field-scale experimental design with controlled replication and statistical analysis. Second, the technical materials used in this study included project documents, product analyses, and case-history data, which are useful for technical interpretation but do not constitute definitive scientific proof of treatment performance. Third, because the study did not directly compare multiple treatment systems under identical operating conditions, the findings should be interpreted as a technical and field-oriented examination rather than as conclusive validation of treatment efficacy.

Nevertheless, this study remains meaningful in that it provides a structured basis for understanding the technical components and possible field applicability of an integrated microbial-chemical system for odor reduction in wastewater treatment. The study may therefore serve as a useful reference for future experimental validation, pilot-scale optimization, and practical implementation.

4. Field Applicability and Integrated Interpretation

4.1. Field Application Conditions and Operational Relevance

The field applicability of the proposed integrated microbial-chemical system can be discussed in relation to the operational conditions under which the treatment agents were applied. As summarized in Table 2, the application of BCP80 and STIMULUS was conducted not as a one-time intervention, but as a staged dosing program consisting of initial dosing, reduced dosing, and weekly maintenance input. This operational structure suggests that the proposed system was intended for continuous management of odor-related conditions rather than for short-term deodorization alone.

Such a dosing strategy is technically meaningful because odor generation in wastewater treatment is strongly affected by dynamic process conditions, including organic loading, oxygen availability, hydraulic fluctuation, and microbial instability (Lebrero et al., 2011). Treatment performance is likely to depend not only on the intrinsic properties of the applied agents, but also on whether their application is maintained in a stable and responsive manner over time (Herrero & Stuckey, 2015). In addition, the staged application pattern is consistent with an integrated treatment concept in which monitoring and control support operational coordination under field conditions (Zarra et al., 2022).

In addition, the staged application pattern is consistent with the overall concept of integrated treatment presented earlier in Figure 2, in which microbial establishment, chemical assistance, and operational control are expected to function in a coordinated manner. Therefore, the field dosing information provides practical context for evaluating the possible relevance of the system under actual wastewater treatment conditions.

4.2. Field-Based Trend of Odor-Related Indicators

The Case-based field materials reviewed in this study showed a decreasing trend in odor-related indicators during the application period of BCP80 and STIMULUS. The observed field trend is presented in Figure 3.

s shown in Figure 3, both H_2S and NH_4 exhibited an overall downward trend during the treatment period. Although the case-history material does not provide a controlled experimental framework, the observed pattern is still meaningful as preliminary field-based evidence suggesting that the integrated application of microbial and chemical agents may contribute to odor reduction under practical operating conditions (Jeon et al., 2009; Zarra et al., 2022).

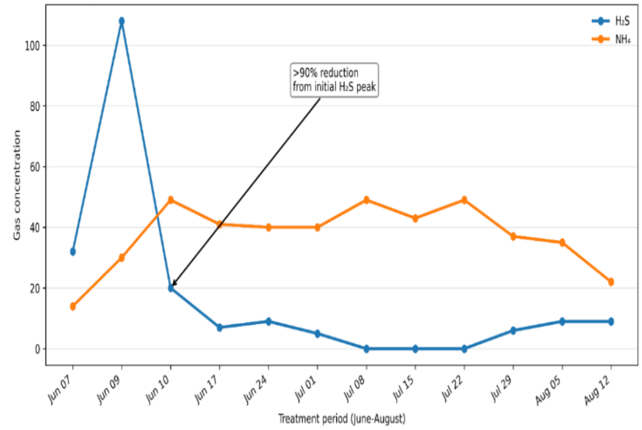

Figure 3: Field-Based Trend of H_2S and NH_4 during the Application of BCP80 and STIMULUS

The interpretation of these data, however, requires caution. The available graph-based information does not include controlled replication, statistical analysis, or fully standardized operating records. In addition, the concentration trend shown in Figure 3 should be understood as a field observation derived from case-history materials rather than as a definitive experimental result. Accordingly, the value of Figure 3 lies primarily in supporting the practical relevance of the proposed system, not in proving treatment efficacy conclusively.

Nevertheless, the decreasing tendency in sulfur- and nitrogen-related indicators remains important because it is consistent with the technical logic discussed in earlier sections. Specifically, microbial degradation may reduce the accumulation of biodegradable substrates associated with odor precursor formation, while chemical assistance may suppress ammonia-related pathways. In this sense, the field trend shown in Figure 3 provides a practically meaningful bridge between the technical basis of the system and its possible real-site applicability (Jeon et al., 2009; Zarra et al., 2022).

4.3. Integrated Interpretation of Treatment Functions

The technical meaning of the proposed system can be more clearly understood when its components are interpreted in relation to their respective functional roles. Rather than relying on a single treatment mechanism, the system appears to combine microbial degradation, chemical assistance, and operational control in a mutually complementary manner (Herrero & Stuckey, 2015; Zarra et al., 2022).

Table 4: Integrated Interpretation of the Technical Roles of the Proposed System

System component	Primary technical role	Relevance to odor reduction	Secondary operational implication
BCP80	Supply of Bacillus-dominant microbial component	Supports biodegradation of organic substrates related to odor precursor formation	May contribute to improved biodegradation stability and possible sludge minimization
STIMULUS	Chemical and microbial complementary treatment component	Provides urease inhibitory activity and supports suppression of ammonia-related odor pathways	May strengthen short-term responsiveness under variable process conditions
Combined application of BCP80 and STIMULUS	Functional complementarity between biological and chemical actions	Addresses multiple odor-related mechanisms simultaneously rather than individually	Supports integrated field application logic
Monitoring and automated dosing	Adaptive operational control based on changing field conditions	Improves responsiveness to odor-generating conditions	Enhances operational continuity and dosing efficiency

Table note: This table presents a technical interpretation based on product analysis, field application materials, and system-level discussion in the present study.

As indicated in Table 4, the proposed technology should not be interpreted as a simple microbial additive. Instead, it is more appropriately understood as an integrated treatment system in which microbial treatment, chemical support, and operational control are linked to address odor generation from multiple directions (Herrero & Stuckey, 2015; Zarra et al., 2022).This interpretation is important because odor formation in wastewater treatment systems rarely results from a single reaction pathway. Rather, it arises from the interaction of organic loading, oxygen limitation, biochemical conversion, and process instability.

Table 4 also clarifies the position of sludge minimization within the present study. Although sludge reduction is not directly verified through quantitative mass-balance analysis in this paper, it may still be regarded as a possible secondary operational implication of improved biodegradation and process stabilization. Therefore, the main focus of the present discussion remains odor reduction, while sludge minimization is treated as a technically relevant but not independently validated implication.

4.4. Operational Significance of Monitoring and Automated Dosing

Another important implication of the proposed system lies in the intended integration of microbial-chemical treatment with monitoring and automated dosing control. As illustrated conceptually in Figure 2, the treatment logic of the system extends beyond the properties of the treatment agents themselves and includes the way in which dosing decisions are linked to field conditions.

This point is important because odor generation is not a static phenomenon. In wastewater treatment facilities, odor intensity and composition may vary depending on influent characteristics, retention time, temperature, dissolved oxygen, redox conditions, and operational disturbances. Under such conditions, fixed dosing schedules or purely manual intervention may not provide sufficient responsiveness. By contrast, an operational framework supported by sensing, monitoring, and automated dosing may improve treatment efficiency by enabling adjustment according to changing site conditions (Zarra et al., 2022; Suriasni et al., 2024).

From a field applicability perspective, this means that the technical value of the proposed system lies not only in microbial composition or chemical function, but also in its compatibility with adaptive operation. Therefore, the integrated microbial-chemical system should be interpreted as an operationally structured treatment approach rather than as a stand-alone product concept (Zarra et al., 2022; Suriasni et al., 2024).

4.5. Implications and Limitations of Field Applicability

Taken together, the materials reviewed in this study suggest that the proposed integrated microbial-chemical system has meaningful technical plausibility and possible field applicability for odor reduction in wastewater treatment. This interpretation is supported by three lines of evidence: the microbial characteristics of BCP80, the concentration-dependent urease inhibitory activity of STIMULUS, and the field-based trend showing decreased H_2S and NH_4 during the treatment period.

At the same time, these findings must be interpreted within the limitations of the available evidence. The present study was not based on a dedicated experimental dataset with controlled replication, control groups, or statistical validation. The field case information used in this study was derived from project-related and case-history materials, which are useful for technical interpretation but do not constitute definitive scientific proof of treatment performance. For this reason, the present discussion should be understood as an assessment of technical basis and field applicability rather than as a conclusive demonstration of treatment efficacy (Lebrero et al., 2011; Herrero & Stuckey, 2015).

Despite these limitations, the study remains meaningful in that it provides a structured interpretation of how microbial treatment, chemical assistance, and adaptive operation may interact in practical wastewater treatment environments.

Future research should therefore focus on pilot-scale or full-scale validation under defined operating conditions, including quantitative evaluation of H_2S, NH_3 or NH_4-N, organic matter indicators, sludge generation, and operational cost (Herrero & Stuckey, 2015; Morello et al., 2022). Such work would provide the evidence needed to translate the present technical interpretation into a more robust field implementation framework.

5. Conclusions

This study examined the technical basis and field applicability of an integrated microbial-chemical system for odor reduction in wastewater treatment. The study focused on odor generation as a major operational issue in wastewater treatment systems and discussed the functional roles of microbial components, chemical assistance, and smart operational control within an integrated treatment framework.

The findings of this study suggest that odor generation in wastewater treatment is closely associated with the formation of hydrogen sulfide, ammonia, and other malodorous compounds under oxygen-limited and biologically unstable conditions. In this context, the proposed integrated microbial-chemical system may be regarded as a technically meaningful approach because it combines microbial degradation, suppression of odor-related biochemical pathways, and adaptive operational control within a unified treatment concept.

The technical materials reviewed in this study indicate that the proposed system is based on the complementary interaction of microbial and chemical functions. The analyzed microbial product contained Bacillus spp. and lactic acid bacteria, while the accompanying treatment component exhibited urease inhibitory activity. These characteristics suggest that the system may contribute to odor reduction by supporting organic matter degradation and suppressing ammonia-related odor formation. In addition, the reviewed field-related materials showed a decreasing trend in odor-related indicators during application, supporting the possible practical relevance of the proposed treatment concept. However, these materials should be interpreted as supportive technical evidence rather than definitive scientific proof, since they do not provide a complete experimental framework with controlled replication and statistical validation.

Another important implication of this study is that the effectiveness of the proposed system is likely to depend not only on the intrinsic properties of the microbial and chemical components, but also on operational strategy. The integration of IoT-based monitoring and automated dosing control may improve treatment responsiveness and operational stability under variable wastewater conditions. Therefore, the proposed technology should be understood as an integrated treatment system rather than as a single-function additive approach.

Overall, this study provides a structured technical understanding of the basis, functional characteristics, and possible field applicability of an integrated microbial-chemical system for odor reduction in wastewater treatment. Although the present study does not provide direct experimental validation, it offers a useful technical foundation for future pilot-scale and full-scale research. Future studies should focus on quantitative validation using indicators such as hydrogen sulfide reduction, ammonia reduction, organic matter removal, sludge generation as a secondary operational parameter, and operational cost efficiency. Such efforts will be essential for establishing the scientific reliability and practical applicability of this integrated treatment approach in wastewater treatment systems.

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