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Hinshelwood Biokinetic Evaluation and SWOT-Based Aesthetic Mitigation of Contact-Stabilization Units for Sustainable Tourism Landscapes

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ABSTRACT

The tourism industry faces high-strength organic waste threatens the very environments that attract visitors. This study proposes Invisible Engineering to integrate wastewater treatment into tourism landscapes as high-performance aesthetic assets. Using the Hinshelwood Equation Model, we evaluated a Contact-Stabilization (CS) system, finding a high microbial growth rate (μ_{max}) and an extreme yield coefficient (Y) of 22.10 mgVSS/mgCOD. While these kinetics allow for rapid organic reduction, they also cause dense sludge accumulation and anaerobic micro-zones that produce rotten egg odors. To mitigate these risks, a SWOT-based Aesthetic Mitigation Analysis suggests a hybrid configuration: a subsurface CS reactor integrated with plant rhizospheres. This system uses root-zone oxygenation to neutralize odors and stabilize biomass, transforming grey infrastructure into a hidden, functional park.

Keywords: *Contact Stabilization, Microbial Kinetics, Aesthetic Mitigation, Sustainable Tourism, Wastewater Management.*

1. INTRODUCTION

The global tourism industry operates within a waste paradox: economic vitality is often bought at the cost of an environmental burden that threatens the destination's primary allure. In high-density clusters, the hospital, restaurant, and café sectors (HORECA) drives a surge in high-strength organic leachate that poses both biological and perceptual threats to a location's green-status [1], [2]. To resolve this, we propose the concept of Invisible Engineering, where advanced biological solutions are repositioned from utilitarian grey-infrastructure to high-performance aesthetic assets.nWhile this study utilizes the Contact-Stabilization system, noted for its compact footprint and resilient biomass [3] as a primary model, the underlying objective is to establish a universal strategic approach for sustainable landmarks.

By employing a SWOT-based Aesthetic Mitigation Analysis, this research evaluates Contact-Stabilization biokinetics alongside visual integration strategies. This dual-track assessment provides a replicable framework, allowing various wastewater technologies to be modified and optimized to support high-value tourism destinations without compromising their landscape integrity.

2. LITERATURE REVIEW

2.1. Wastewater Challenges in Indonesian Tourism

The wastewater management crisis in Indonesian tourism is compounded by a double burden where domestic effluents from the HORECA sector intersect with the untreated discharge of high-strength leachate. In coastal destinations like Sanur, Bali, the rapid expansion of tourism facilities has led to organic pollution levels that categorize certain areas as heavily polluted, with BOD and nutrient concentrations far exceeding environmental standards [4], [5]. This challenge is exacerbated by the presence of leachate, which, as a byproduct of the massive organic waste generated during peak seasons, contains extreme Chemical Oxygen Demand (COD) and inhibitory substances that are

significantly more difficult to treat than standard domestic sewage [6].

2.2. Standard Wastewater and Leachate Treatment Systems

Indonesia enforces strict domestic wastewater and leachate treatment standards via PERMEN LH 11/2025, mandating BOD ≤30 mg/L, COD ≤100 mg/L, and TSS ≤30 mg/L for discharge from tourism facilities like hotels before release to water bodies or sewers. Leachate from tourism-area landfills requires similar limits (BOD ≤150 mg/L for septage facilities), with advanced treatments like contact-stabilization or MBRs essential to prevent groundwater/coastal contamination in high-traffic zones. These invisible backend systems are urgent for sustainable tourism, as untreated leachate spikes pollutants 10-100x over limits, harming surrounding area and visitor health [6], [7].

2.3. Contact-Stabilization System

The Contact-Stabilization system is an advanced biological wastewater treatment configuration designed to efficiently reduce organic pollutants, particularly in high-strength waste like landfill leachate. The Process devided into contact phase and stabilization phase. This configuration is highly effective because it requires a smaller footprint compared to conventional activated sludge systems while maintaining high resistance to varying organic loads [3].

2.4 Concept of Invisible Engineering

In themed environments and tourism, invisible engineering is a strategic design philosophy that conceals complex utilities to preserve the immersive quality of the destination [8]. Within this framework, wastewater treatment is seamlessly integrated into the tourism landscape, ensuring that backend functional efficiency never compromises the visitor experience or visible aesthetics.

3. METHOD

This research employs a dual-track methodological framework to evaluate the integration of wastewater treatment into sustainable tourism landscapes. The study is divided into two primary phases: technical biokinetic modeling and strategic aesthetic mitigation analysis.

The first phase evaluates the stabilization unit of the Contact-Stabilization process using the **Hinshelwood Equation Model**. This model is utilized to determine the microbial growth kinetics and substrate utilization rates under specific reactor operational parameters. The governing equation for the specific growth rate (μ) is defined in Equation 1.

$$\mu = \mu_{\max} \frac{S_{st}}{K_s + S_{st}} \left(\frac{P_m}{P_m - P} \right) \quad \text{..... (1)}$$

Experimental data was derived from laboratory-scale reactors with defined parameters (Table 1). These values allow for the calculation of the maximum specific growth rate (μ_{max}) and the yield coefficient (Y), which serve as the technical baseline for potential operational risks.

Table 1. Operational Parameter of Contact Stabilization

Parameter	Value	Unit
Contact Discharge	80	L/day
Stabilization Discharge	40	L/day
Recirculation Ratio	0.5	-
HRT, Contact	0.5 – 1	Hours
HRT, Stabilization	3 – 6	Hours
*TSS	2,072 – 4250.05	mg/L
*COD	457.4 – 491.24	mg/L
*NH3	89.98 – 489.78	mg/L

Source: [3]

The second phase employs a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis to develop a strategic roadmap for Invisible Engineering. This methodology systematically categorizes the biokinetic findings into internal and external factors:

1. Internal Factors: Evaluation of technical strengths (e.g., rapid treatment) and weaknesses (e.g., extreme sludge production) based on Y and μ_{max} values.
2. External Factors: Identification of opportunities for landscape integration and threats such as seasonal odor deterioration or visual degradation.

By cross-referencing these variables through a Strategic Matrix, the study generates specific Strategy Actions (S-O, W-O, S-T, W-T) to transform traditional grey infrastructure into a functional, subsurface aesthetic asset. This ensures compliance with PERMEN LH11/2025 while preserving the immersive quality of tourism destinations.

4. FINDINGS AND DISCUSSION

4.1. Stabilization Performance on Leachate Treatment

Based on laboratory-scale analysis and biokinetic evaluation using the Hinshelwood Equation, the maximum specific microbial growth rate (μ_{max}) was determined to be 4.05 day^{-1}. The yield coefficient (Y) reached 22.10 mgVSS/mgCOD, while the half-saturation constant (K_s) for the substrate in the stabilization unit was 18.25 mg/L.

The observed yield coefficient (Y) of 22.10 mg VSS/mg COD significantly deviates from the theoretical range typically reported for aerobic biological systems (0.4 to 0.6 mgVSS/mgCOD). This substantial value suggests that the increase in Volatile Suspended Solids (VSS) is not solely attributable to microbial proliferation (biomass growth) but is likely driven by extra-metabolic

mechanisms. In this context, the high Y value indicates a predominance of biosorption, where organic matter and particulate COD are physically entrapped within the Extracellular Polymeric Substances (EPS) matrix or adsorbed onto the microbial cell walls [9].

The observed μ_{max} of 4.05 day^{-1} indicates a high level of microbial metabolic activity, necessitating a corresponding increase in the Oxygen Uptake Rate (OUR). Under standard aeration capacities, such rapid biomass proliferation may lead to a localized depletion of Dissolved Oxygen (DO), creating a deficit between oxygen supply and biological demand. This is further exacerbated by the high Y, which results in a dense and heterogeneous sludge blanket.

From a physical standpoint, this kinetic performance manifests as a high-density mixed liquor with rapid sludge accumulation rates. The stabilization unit is characterized by the formation of large, dense macro-flocs consistent with Hinshelwood biokinetic stability. However, the potential for lipid-induced flotation exists if the high yield is a result of trapped fats, oils, and grease (FOG), the reactor may exhibit a persistent greyish-white scum layer on the surface [10], [11]. Such conditions necessitate frequent sludge wasting to prevent secondary contamination of the effluent due to solids carryover.

Due to the increased thickness of the sludge flocs and the viscous nature of the mixed liquor, mass transfer resistance limits the diffusion of oxygen into the deeper layers of the biomass. This creates anoxic and anaerobic micro-zones within the stabilization unit, facilitating the onset of anaerobic fermentation [12]. Consequently, the initial earthy odors, typical of aerobic actinomycetes, will likely transition into more pungent characteristics. The emergence of hydrogen sulfide (H_2S) and volatile fatty acids (VFAs) from the anaerobic mineralization of excess biomass will result in rotten egg or sour/acidic odors, signaling a shift in the reactor's redox environment.

4.2. SWOT in Aesthetic Mitigation Analysis

The biokinetic parameters identified in the stabilization unit, specifically the high maximum growth rate (μ_{max}) and the extreme yield coefficient (Y), indicate a high-performance system that carries significant aesthetic risks if left unmanaged. While these kinetics ensure rapid organic reduction, the resulting dense biomass proliferation and potential for anaerobic micro-zones necessitate a robust physical and strategic framework to prevent operational failure. To systematically evaluate these technical variables within a tourism landscape context, a SWOT analysis was conducted. This analysis, detailed in Table 2, categorizes the internal technical behaviors and external perceptual risks, serving as the foundation for the Invisible Engineering integration strategy.

Table 2. SWOT analysis of Contact-Stabilization

Category	Analysis
Strength	Rapid Treatment: High μ_{max} allows for quick organic reduction. Compact Design: Smaller footprint facilitates easier Invisible Engineering integration.
Weakness	Extreme Sludge Production: High yield leads to rapid solids accumulation and potential carryover. Oxygen Diffusion Resistance: Dense flocs create anaerobic micro-zones
Opportunities	High Biosorption: Utilizing the EPS matrix for physical entrapment of particulate COD. Subsurface Potential: Ability to bury the reactor to minimize visual impact.
Threats	Odor Deterioration: Risk of H_2S and VFA production (rotten egg smells) due to anaerobic shifts. Visual Degradation: Potential for surface scum or grease layers.

To resolve these conflicts and align technical performance with the Invisible Engineering philosophy, the internal and external factors from the SWOT are cross-referenced to develop a targeted mitigation roadmap. This study proposes a hybrid configuration: a subsurface Contact-Stabilization reactor integrated with an Integrated Attached Growth (IAG) system utilizing plant rhizospheres. The specific strategic actions derived from this integration, which transform potential threats into managed assets, are systematically outlined in the Strategic Matrix in Table 3.

Table 3. Strategic Matrix for Hybrid Root-Based CS Integration

Strategy	Strategy Actions
S-O	Subsurface Deployment: Utilize high microbial activity and compact design to bury the reactor beneath a landscaped park, removing the perceptual burden of waste from sight
W-O	Root-Based Filtration: Use plant roots as a physical matrix to trap excessive sludge, turning high biomass production into a stabilized biological filter.
S-T	Aesthetic Protection: Direct high-performance growth into the rhizosphere to prevent surface scum and grease layers, ensuring the system remains a visual asset for the tourism sit
W-T	Odor Neutralization: Mitigate anaerobic rotten egg smells by using root-zone oxygenation to prevent the fermentation of dense sludge blankets

5. CONCLUSIONS

Based on the biokinetic evaluation where the yield coefficient, it is strongly recommended that the standalone Contact-Stabilization system be modified into a hybrid Integrated Attached Growth (IAG) configuration to ensure operational and aesthetic viability in tourism clusters. Scientific analysis indicates that the high microbial growth rate triggers rapid oxygen depletion and mass transfer resistance within dense sludge blankets. To mitigate these risks, the integration of plant rhizospheres is recommended as a strategic solution as a natural physical matrix to stabilize excessive biomass and provide radial oxygen loss, which prevents the anaerobic mineralization responsible for H_2S and VFA odors.

Furthermore, the adoption of an Invisible Engineering framework, specifically by situating the hybrid reactor beneath a functional park, is advised to neutralize the visual perceptual burden of wastewater infrastructure. This integrated approach is essential for high-value tourism destinations to meet the stringent discharge standards while preserving landscape integrity and the visitor experience**.**

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