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Application of Unmanned Aerial Vehicles in Assessing the Current Condition and Closure Design of Da Mai Landfill (Vietnam)

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Abstract

Municipal solid waste (MSW) landfills remain a major source of greenhouse gas emissions, leachate pollution, and land degradation, particularly in low- and middle-income countries where many sites operate beyond their design capacity. This study proposes an integrated and low-cost framework combining unmanned aerial vehicle (UAV) photogrammetry with environmental assessment to support landfill closure planning. Using the Da Mai landfill (Vietnam) as a case study, high-resolution orthomosaics and a digital surface model (DSM) were generated with a vertical RMSE of 5 cm. UAV imagery and terrain analysis revealed major operational problems, including uncontrolled filling, steep, unstable slopes, damaged leachate drainage, surface ponding, and inadequate daily cover. The landfill was estimated to contain 229,602 m^3 of waste in the upper part, with elevations up to 8.5 m, exceeding the design limit by 1.5 m. Based on UAV-derived spatial parameters, potential greenhouse gas emissions and annual leachate generation were estimated at 62,710 tCO_2e/year and 33,729

m^3, respectively. These results indicate the need for early closure intervention at an elevation of 8.5 m. Compared with conventional surveying, the proposed approach improves spatial coverage, reduces field time, and provides practical engineering inputs. The study demonstrates that UAV photogrammetry can support both the diagnosis of landfill problems and closure planning. Additionally, further research should explore UAV applications in monitoring landfill operations pre- and post-closure.

Keywords

Digital surface model; engineering decision support; landfill closure design; solid waste management; UAV photogrammetry

1. Introduction

Global economic growth, rapid urbanization, and changing consumption patterns have led to a significant increase in municipal solid waste (MSW) generation worldwide. Despite advances in waste treatment technologies, landfilling remains the dominant disposal method, particularly in low- and middle-income countries (LMICs), where financial and technical constraints limit the implementation of advanced treatment solutions [1]. Although landfilling offers advantages such as low cost and operational simplicity, aging or poorly managed landfill facilities pose serious environmental and public health risks, including greenhouse gas emissions, leachate contamination, and long-term land degradation [1-3]. In Vietnam, more than 70% of MSW is disposed of in landfills, many of which lack adequate environmental protection systems such as liners, leachate collection infrastructure, and gas recovery facilities [2, 3]. As a result, numerous landfills operate beyond their design capacity, leading to uncontrolled emissions and environmental pollution. Conventional ground-based surveying methods used for landfill monitoring are often time-consuming, costly, and potentially unsafe, especially in unstable landfill environments. These limitations restrict the availability of reliable spatial data required for informed landfill closure planning and environmental risk mitigation.

In recent years, unmanned aerial vehicles (UAVs) have emerged as a promising tool for environmental monitoring and spatial data acquisition. UAV photogrammetry enables rapid generation of high-resolution orthomosaics and digital surface models (DSM) with centimeter-level accuracy. Previous studies have demonstrated the effectiveness of UAVs for landfill geomonitoring, terrain mapping, and volumetric estimation [4, 5]. Other studies have explored UAV-mounted thermal and multispectral sensors for identifying methane emission hotspots and monitoring landfill surface temperature variations [6-8]. Additionally, UAV-based approaches have been applied to estimate greenhouse gas emissions and assess landfill environmental performance [9, 10].

Despite these advances, most existing studies focus primarily on environmental monitoring and mapping rather than on integrating UAV-derived data into landfill closure planning and engineering decision-making. In many cases, UAV data are used to describe landfill conditions without translating spatial information into practical closure strategies. This limitation highlights a significant research gap, particularly in developing countries where cost-effective and data-driven landfill closure approaches are urgently needed. Recent advancements in environmental monitoring have demonstrated the efficacy of deep learning, such as memory-efficient CNNs for smart waste classification [11]. Furthermore, the stability and performance of UAV platforms have been significantly enhanced through sophisticated control algorithms, such as Fractional Order Extended State Observers [12]. However, the integration of these high-fidelity spatial products into landfill closure and rehabilitation planning remains limited and insufficiently documented.

Recently, the adoption of UAV technology for environmental monitoring in Vietnam has expanded significantly. UAV imagery, often integrated with deep learning models, has been effectively deployed to detect coastal plastic waste and map environmental pollution across complex terrains [13]. In industrial sectors, UAV photogrammetry has proven reliable for quarry monitoring and waste dump assessments, providing high-precision volumetric data and terrain analysis [14]. Specifically in the context of landfill management, the efficacy of UAV-based approaches has been demonstrated through recent studies on unsanitary, small-scale sites. For instance, at the Quang Loi landfill, high-resolution DSMs generated from UAV data facilitated precise waste volume estimates and operational risk assessments, proving a cost-effective alternative to traditional surveying [15]. Furthermore, the transition from monitoring to rehabilitation planning was explored at the Cam Ha landfill, where UAV-derived data supported the conceptualization of a ‘green landfill’ closure model that emphasizes ecological restoration and natural treatment components [16]. Previous studies have demonstrated the effectiveness of UAV-based photogrammetry for landfill surface mapping and volumetric estimation. However, most of these studies primarily focus on geometric characterization and monitoring purposes, with limited integration into environmental impact assessment or engineering design applications. In addition, conventional approaches for estimating greenhouse gas emissions and leachate generation are often conducted independently of high-resolution spatial data, resulting in increased uncertainty in site-specific evaluations. Despite these advancements, the practical integration of high-resolution UAV data into detailed engineering closure designs and systematic environmental rehabilitation planning remains limited, particularly for aging municipal solid waste landfills that have exceeded their design capacities.

To address these gaps, this study makes the following key contributions: (i) Developing an integrated UAV-DSM workflow for high-resolution topographic reconstruction and volumetric estimation of a legacy landfill site; (ii) Coupling UAV-derived geometric data with first-order decay modeling to quantify potential greenhouse gas (GHG) emissions and leachate generation under site-specific conditions; (iii) Demonstrating how UAV-derived datasets can inform preliminary landfill closure design, including grading strategies, drainage layout, and ecological rehabilitation planning; (iv) providing quantitative validation against conventional ground-based surveys. By linking UAV-based mapping with environmental assessment and closure planning, this study aims to provide a scalable and cost-effective approach to landfill rehabilitation in Vietnam and similar contexts.

2. Materials and Methods

2.1 Study Area

The Da Mai landfill is the primary municipal solid waste disposal facility serving Bac Ninh Province, northern Vietnam. The landfill, covering about 6.5 ha, has been operational since 2006, as shown in Figure 1. Originally designed as a sanitary landfill equipped with a bottom liner and leachate collection system, the facility has gradually exceeded its design capacity due to increasing waste generation and limited operational control.

Figure 1 Location of Da Mai landfill.

2.2 Integrated Methodology Workflow

The research methodology is structured into four integrated phases, as illustrated in the general block diagram (Figure 2). This workflow transitions from raw spatial data acquisition to evidence-based engineering design.

- **Phase 1: Data Acquisition and Pre-processing**: Dual-source data was utilized. (1) The baseline topography (H_i^B) was reconstructed from the as-built drawings of the landfill bottom, and (2) concurrent site conditions were captured via a UAV flight (DJI Phantom 4 RTK) to generate high-resolution imagery.
- **Phase 2: Digital Reconstruction and Filtering**: UAV imagery was processed using Agisoft Metashape to produce a DSM and an Orthomosaic.
- **Phase 3: Environmental Assessment**: The DSM was initially used to assess the current operational problems of the landfill. Then, the data extracted from the DSM were used to calculate waste volume, estimate Greenhouse Gas (GHG) emissions, and annual leachate volume to inform decisions about landfill closure design.
- **Phase 4: Conceptual Closure**: Unlike traditional mapping, the spatial outputs (slopes, overcapacity zones, and drainage patterns) and waste volume were used to inform the development of the closure scheme.

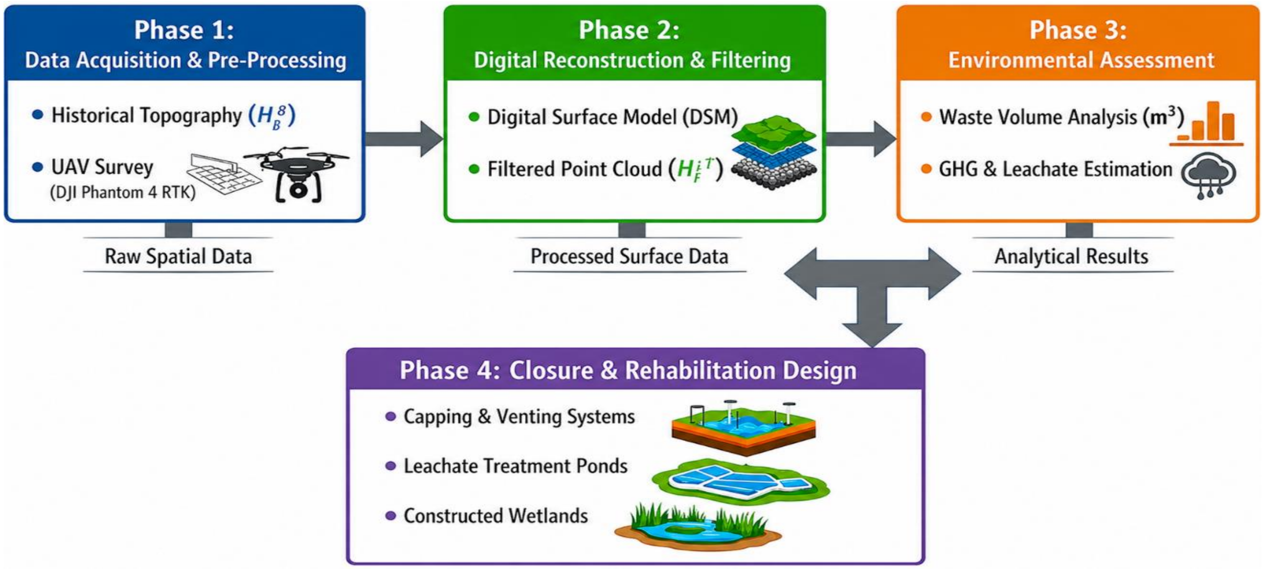

Figure 2 Workflow of the processing.

2.3 UAV Data Acquisition and Processing

High-resolution aerial data were acquired using a DJI Phantom 4 Pro v2 UAV equipped with a 20-megapixel, 1-inch CMOS sensor. Flight missions were planned using DJI GO 4 and Drone Deploy to ensure systematic site coverage, with 80% longitudinal and 70% lateral image overlaps (Figure 3). The flight altitude was set at 60 m above ground level, resulting in a ground sample distance (GSD) of approximately 2.0 cm per pixel, based on the camera focal length, sensor size, and flight height.

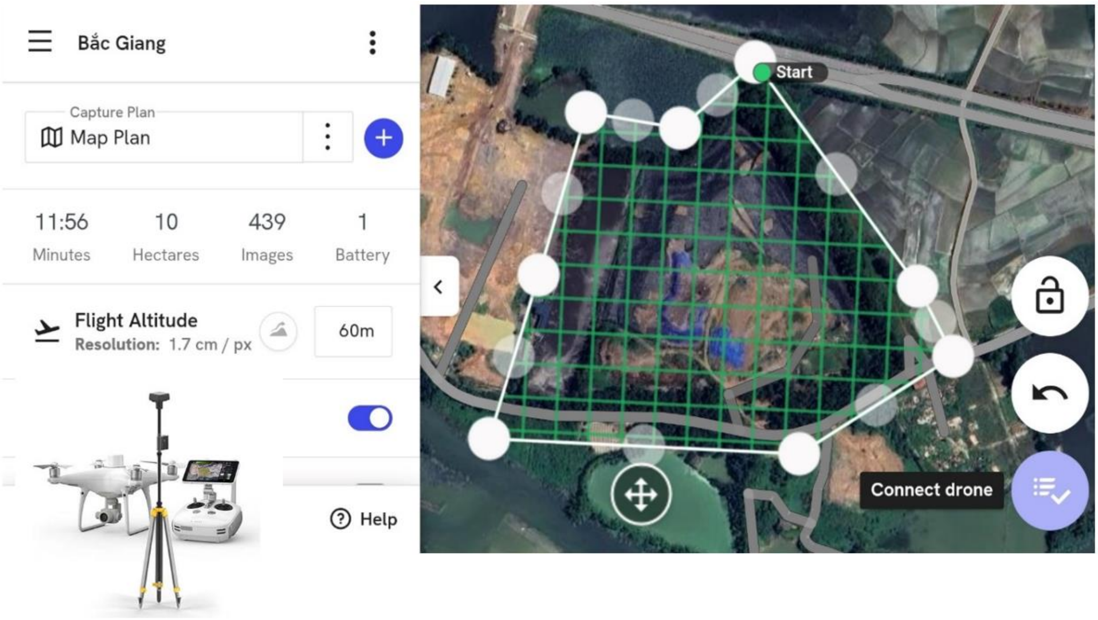

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Figure 3 UAV, GPS device, and software used for survey.

To accurately georeference the photogrammetric products, a network of nine ground control points (GCPs) was established across the landfill surface. The GCPs were marked in the field using high-contrast targets measuring 60 × 60 cm, a size selected based on the image scale to ensure clear visibility and precise centroid identification in the UAV imagery. The coordinates of the GCPs were measured using Trimble R8S GNSS receivers operating in real-time kinematic (RTK) mode, achieving horizontal and vertical accuracies of ±8 mm and ±15 mm, respectively.

Photogrammetric processing was performed using Agisoft Metashape software, including image alignment, dense point cloud generation, DSM creation, and orthomosaic generation. GCPs were also used to assess positional accuracy using root-mean-square error (RMSE).

2.4 Waste Volume Estimation

To estimate waste volume, the original landfill base surface was reconstructed from historical engineering drawings combined with surrounding terrain elevations derived from UAV-generated DSM. The reconstructed base surface was assumed to be a linear interpolation between boundary elevations and design contours. Non-waste features such as access roads, drainage structures, and vegetation were manually identified and removed using GIS-based classification and visual interpretation. The difference between the reconstructed base surface and the current DSM was then calculated to determine waste thickness and total waste volume. To improve the robustness of the estimation, the landfill surface was divided into a regular grid of 10 m × 10 m cells [15]. The grid size was selected to balance spatial resolution and computational efficiency, consistent with previous UAV-based landfill studies [5, 17]. For each grid cell, waste thickness was calculated as the elevation difference between the DSM surface and the reconstructed base surface. The total waste volume V (m^3) was then calculated as recommended by [15]:

$$V = \Sigma[Ai \times (H_i^T - H_i^B)] \tag{1}$$

Where:
Ai: area of grid cell (m^2).
H_i^B: base elevation (m) obtained from as-built drawings.
H_i^T: surface elevation (m) obtained from DEM data.

Non-waste features, including vegetation and infrastructure, were manually removed during DSM preprocessing to reduce estimation errors.

2.5 Greenhouse Gas Emission Estimation

The potential greenhouse gas (GHG) emissions from the Da Mai landfill were estimated using a mass-balance model [18, 19]. The annual emissions (tCO_2e) were calculated as follows:

$$GHG_L = W\left[\left(DOC \times DOC_f \times F_1 \times C_{CH_4} - R\right) \times (1 - OX)\right] \times GWP \tag{2}$$

Where:
W: Total waste mass (ton).
DOC: Degradable organic carbon, selected to reflect the high organic fraction typical of unsorted MSW in Northern Vietnam.
DOC_f: the fraction of degradable organic carbon dissimilated.
F_1: the methane fraction of landfill gas.
C_{CH_4}: the conversion rate of carbon to methane.
R: the amount of landfill gas recovered or flared in the given year.
OX: the oxidation factor (0.1 for sanitary landfill).

GWP: the global warming potential used to estimate CO_2e from methane.

According to the Australian National Greenhouse Accounts Factors (2021) [19], the parameter values were selected as follows: DOC = 0.15 for organic waste, DOC_f = 0.5, F_1 = 0.5, OX = 0.1, C_{CH_4} = 1.336; and GWP_{CH_4} = 28.

2.6 Leachate Generation Estimation

Annual leachate generation was estimated using a simplified water balance approach, which accounts for landfill surface area and regional rainfall characteristics. This method accounts for the water entering the landfill (primarily rainfall) and the portion that infiltrates the waste mass to become leachate. The formula for the annual volume of leachate is [20]:

$$Q = k \times R \times A \tag{3}$$

Where:
Q: is the annual volume of leachate (m^3/year).
k: is the dimensionless leachate generation coefficient, which accounts for water losses due to evaporation and surface runoff.
R: is the annual rainfall.
A: is the landfill's surface area (m^2).

3. Results and Discussion

3.1 UAV-Based Spatial Reconstruction: Accuracy Validation and Comparative Performance

The photogrammetric processing of the UAV survey successfully collected a dataset of 439 high-resolution aerial images, covering the entire surface area and the surrounding region of the Da Mai landfill in approximately 12 minutes. The resulting high pixel density allows for clear reconstruction of the landfill's geometric features and even the smallest surface deformations, providing a reliable database for digital elevation modeling (DEM) and quantitative analyses of waste volume.

The vertical accuracy of the DSM was verified using 9 GCPs distributed across the site, yielding an RMSE of 5 cm (details are provided in Table S1 in the supporting data). This level of precision meets the standards of the American Society for Photogrammetry and Remote Sensing (ASPRS, class 1) for the quality assessment of DEM and DSM. Therefore, it is suitable for quantifying waste volume in the landfills, where even minor vertical deviations can lead to significant errors in volume estimation [14, 17]. The experimental results in this study further reinforce the evidence that UAV-based DSM/DEM production achieves accuracy comparable to that of traditional total station surveying methods. Furthermore, as detailed in Table 1, the UAV-RTK method offers significant advantages by significantly shortening field survey time (by approximately 95%), saving manpower, and ensuring absolute safety for technicians thanks to its non-contact observation method. This confirms the effectiveness and reliability of UAVs in providing real-time spatial data for landfill management and closure design.

Table 1 Performance comparison between UAV Photogrammetry and Conventional Topographic Surveying.

Comparison Metric	**Conventional Surveying (Total Station)**	**Proposed UAV-RTK Method**	**Improvement/Significance**
Sampling Density	Low (~1 point/ 5-10 m) [21, 22]	Extreme High (3,500 pts/m^2)	Provides a continuous surface for precise volume calculation.
Vertical Accuracy (RMSEz)	1.0-2.0 cm [21]	4.8-5.2 cm [23, 24]	Meets ASPRS Class 1 standards for landfill engineering [23].
Data Acquisition Time	2-3 days (Full site) [22]	25-30 minutes [5, 22]	95% reduction in field exposure and labor cost.
Terrain Representation	Interpolated (Sparse) [21]	Real-world DSM [17]	Captures micro-topography; reduces volume uncertainty [5, 17].
Safety	Low (Direct contact with waste/gas) [1]	High (Non-contact/Remote) [24]	Minimizes health risks from hazardous landfill environments.

To address concerns about surface contamination, a rigorous point cloud filtering process was applied. Non-waste features, including operational structures, heavy machinery, and dense peripheral vegetation, were manually classified and excluded from the final surface model (H_i^T). This ensured that the reconstructed topography represents the actual waste mass, minimizing the risk of volumetric overestimation common in automated photogrammetric outputs. The UAV-derived DEM and contour surface of the Da Mai landfill are presented in Figure 4, highlighting the irregular topography and elevation variations across the site.

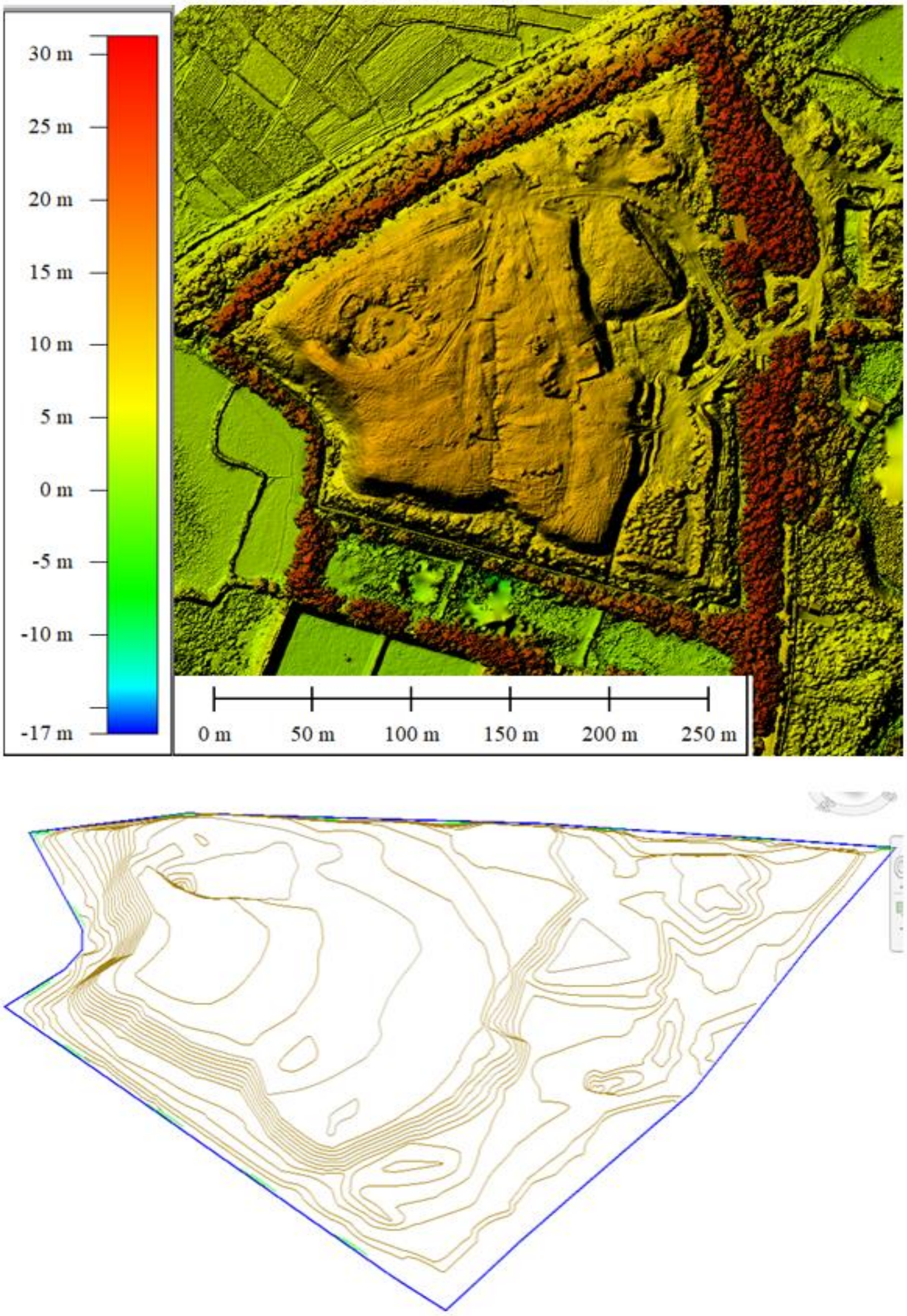

Figure 4 Digital elevation model and contour surface of Da Mai landfill.

While conventional methods remain accurate at specific points, they often fail to capture the complex, irregular micro-topography of overfilled landfills [17]. The UAV-derived DSM provides a continuous topographic fabric, which is essential for identifying localized "hotspots" of overcapacity that are typically missed by sparse point interpolation. However, UAV photogrammetry is inherently limited to capturing surface morphology and cannot detect subsurface anomalies or underground voids. The accuracy of volumetric results depends on the landfill cell bottom structure. Therefore, the waste volume and environmental results presented in the following sections should be understood as modeled potential risks rather than absolute, in-situ-validated measurements.

A vertical RMSE error of 5 cm observed in this study affects volumetric and environmental estimates. Given the landfill surface area, this vertical uncertainty corresponds to a potential volume variation of approximately ±2%. Therefore, the modeled methane emissions and leachate generation rates presented in the following sections should be interpreted within this error range to ensure a cautious approach to environmental calculations.

3.2 The Current Problems

3.2.1 The Current Operational Problems and Volumetric Overcapacity

It should be noted that the greenhouse gas emissions and leachate generation values reported in this study were derived from simplified modeling approaches based on UAV-derived spatial data and literature parameters. Therefore, these results are intended as preliminary indicators for environmental risk screening.

The UAV-derived DSM enabled a high-resolution reconstruction of the current landfill morphology, revealing substantial deviations from the original design configuration. The integration of orthomosaic imagery with DSM analysis provided both quantitative elevation data and visual evidence of operational deficiencies across the site (Figure 5).

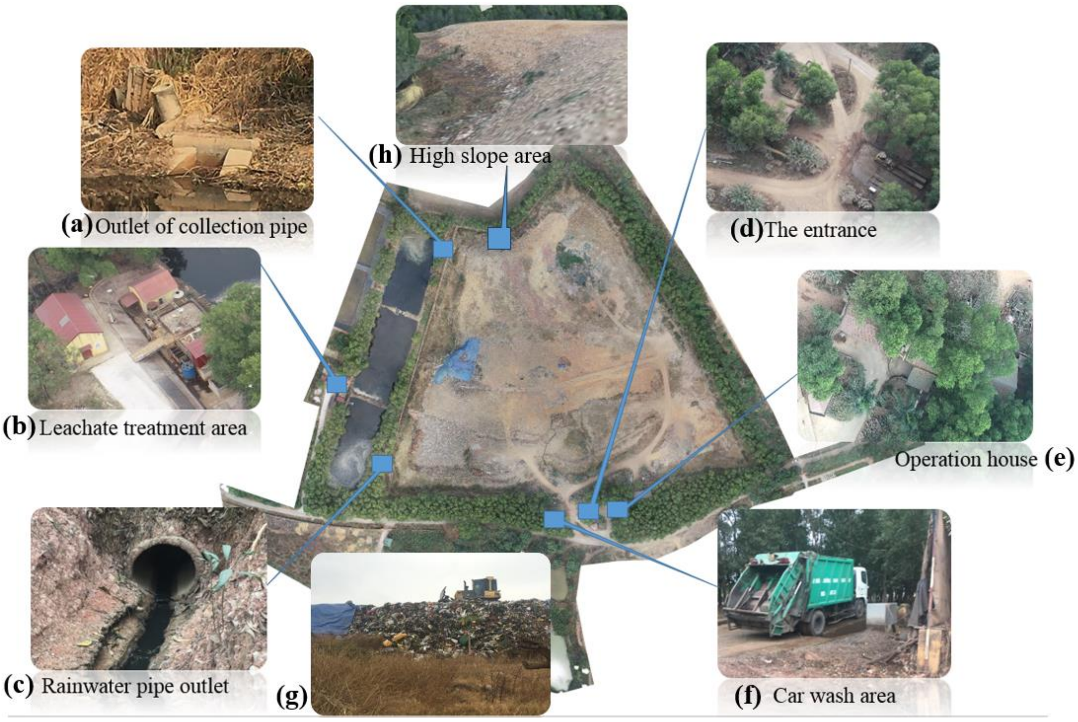

Figure 5 Current status of Da Mai Landfill.

The spatial analysis indicates that the landfill has undergone uneven and uncontrolled filling, resulting in significant morphological instability. The northern sector has the highest elevation and is characterized by excessively steep side slopes (>1:1), exceeding the recommended design range of 1:2-1:3 [4]. These over-steepened slopes increase the risk of slope failure, particularly under high rainfall conditions. Field observations confirm the presence of localized landslides near the leachate conveyance pipeline (Figure 5h), indicating that slope instability is not merely theoretical but is already manifesting in practice.

In addition to structural instability, the UAV imagery reveals clear signs of malfunctioning leachate management infrastructure (Figure 5a). Surface drainage channels contain visibly contaminated leachate, suggesting pipe damage, blockage, or differential settlement. Furthermore, the receiving pond system exhibits dark, stagnant wastewater (Figure 5), indicating that the treatment capacity has been exceeded. These conditions imply intensified anaerobic decomposition and increased potential for odor dispersion and secondary pollution.

Operational practices at the site also deviate significantly from standard landfill management protocols. The UAV-derived surface texture and field observations indicate that waste is deposited in thick layers (>2 m) before soil covering, rather than in controlled thin lifts (Figure 5g). In some areas, the absence of adequate daily cover and inactive washing facilities further reflects poor operational control, increasing environmental exposure and sanitary risks.

From a quantitative perspective, the DSM analysis confirms severe volumetric overcapacity. The average landfill elevation reaches approximately 8.5 m, exceeding the design elevation by about 1.5 m, while peak elevations are up to 3.5 m above the permitted limit. Using a 10 m × 10 m grid-based differential analysis between the current surface and the reconstructed base level, the total waste volume above the original design surface was estimated at 229,602 m^3. Compared to the initial design capacity of approximately 150,000 m^3, this represents an overcapacity of more than 50%. Importantly, the spatial distribution of this excess volume is highly heterogeneous, with both overfilled and underfilled zones coexisting across the site. This uneven filling pattern reflects the absence of systematic operational planning and contributes to differential settlement, slope instability, and inefficient use of landfill space.

Such volumetric exceedance has direct engineering and environmental implications. The excessive waste load increases internal stress on the landfill body, potentially compromising the stability of perimeter embankments and increasing the risk of structural failure. Moreover, overcapacity conditions reduce the effectiveness of leachate collection and gas control systems, thereby exacerbating environmental risks. These findings provide a critical quantitative basis for subsequent environmental risk assessment and for parameterizing closure strategies.

3.2.2 Environmental Risk Assessment: Modeled GHG Emissions and Leachate Generation

Utilizing these volumetric estimates alongside the mass-balance parameters defined in Section 2.5, the potential methane generation was quantified. Using the total waste mass of 206,642 tonnes, the annual GHG emissions were calculated at approximately 62,710 tCO_2e. This substantial atmospheric flux—calculated with a GWP_{CH4} of 28 and DOC of 0.15 highlights the significant environmental liability of the site in the absence of an active gas collection system.

Leachate production remains a critical concern for the Da Mai facility due to its overcapacity and potentially compromised capping integrity. Using the water balance method, which accounts for the UAV-mapped surface area (6.5 ha) and local meteorological data (annual rainfall of 1,600 mm), the annual leachate generation was estimated at 33,729 m^3.

The high spatial resolution of the UAV-DSM allowed for the identification of surface depressions where rainwater tends to pond, thereby increasing infiltration rates beyond standard engineered assumptions [16]. The modeled leachate volume suggests a substantial risk of groundwater contamination, especially given the observed encroachment of waste into peripheral drainage zones discussed in Section 3.2. These quantitative findings provide the necessary evidence base for the sizing of the multi-stage leachate treatment system proposed in the rehabilitation scheme [25].

To enhance the accuracy of methane generation potential, parameters such as the decay rate (k) and methane generation capacity (L_0) were cross-referenced with the US EPA Landfill Gas Energy Project Development Handbook [26]. This alignment ensures that the estimations account for the technological and climatic nuances of landfill gas (LFG) collection systems, which are critical for determining the feasibility of gas-to-energy components.

3.3 Data-Driven Conceptual Closure and Rehabilitation Design

The conceptual closure and rehabilitation framework for the Da Mai landfill was developed directly from the operational deficiencies and environmental risks identified in Sections 3.2.1 and 3.2.2. By integrating UAV-derived DSM data, a site-specific conceptual engineering scheme was formulated, as illustrated in Figure 6, Figure 7, and Figure 8.

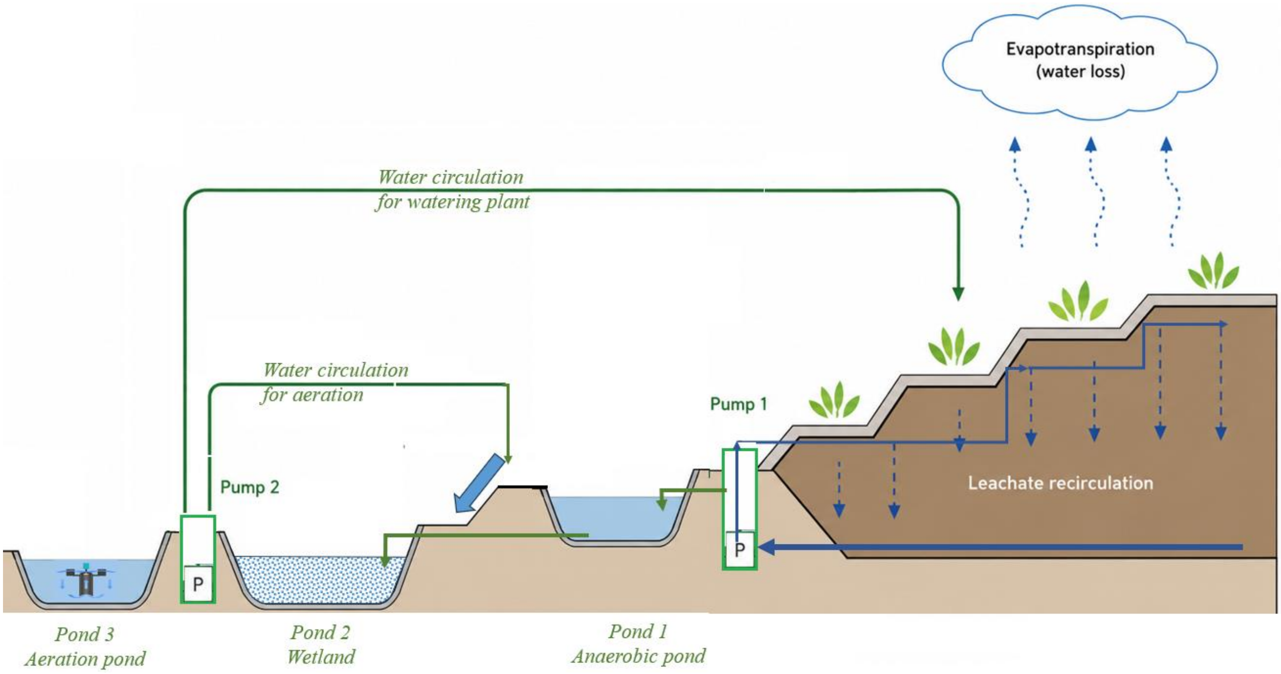

Figure 6 Principle of the design of green landfill.

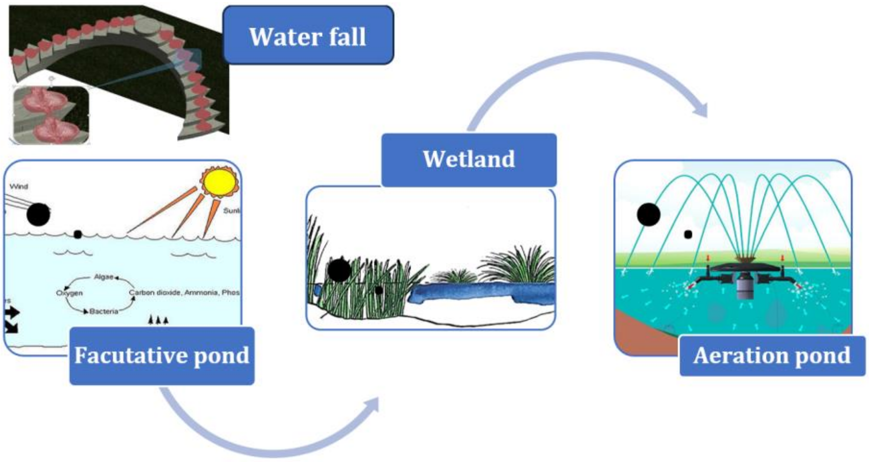

Figure 7 Diagram of the leachate treatment system.

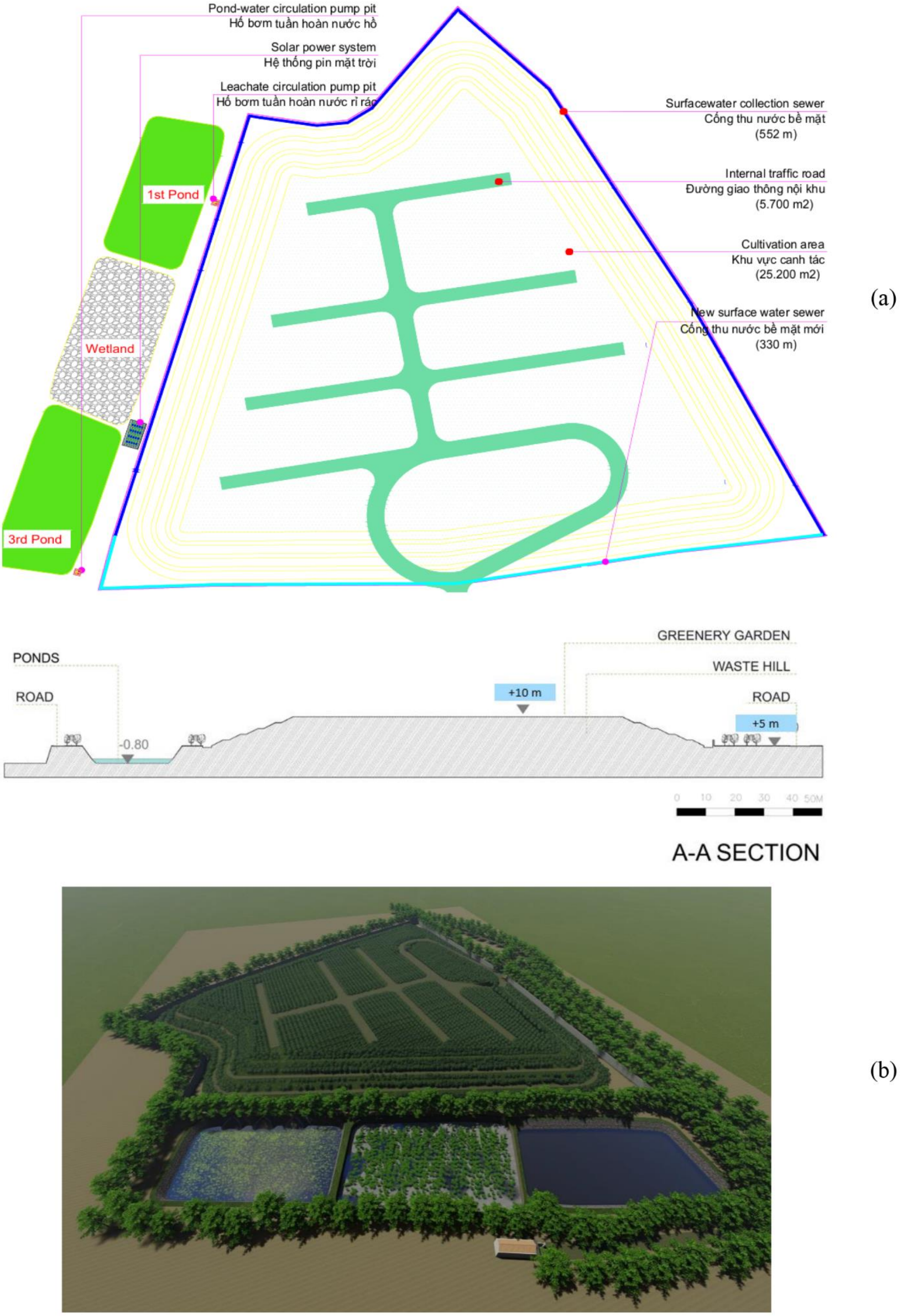

Figure 8 Closure design for Da Mai landfill: (a) Component of the landfill and (b) 3D-Design of landfill.

As presented in Figure 6, the proposed approach follows the "green landfill" principle, which integrates engineered containment systems with controlled biological processes to enhance in situ stabilization of the waste mass. This concept is particularly relevant for the Da Mai landfill, where high organic content and excessive leachate strength make direct treatment costly and inefficient.

The UAV-derived DSM (Section 3.2.1) revealed significant overcapacity, irregular topography, and localized slope instability, particularly in the northern sector. These spatial findings directly informed the geometric restructuring of the landfill body. The design utilizes current surface elevations as the baseline, incorporating a 1.5 m final cover layer to reach a target post-closure elevation of 10.0 m. To achieve this uniform profile, a cut-and-fill strategy was applied where areas exceeding 8.5 m in elevation were graded and redistributed to lower-lying sectors. As illustrated in Figure 8b, the final landform is reprofiled to achieve stable slopes (approximately 1:3) of the embankment and a more uniform elevation distribution, thereby reducing the risk of slope failure and improving long-term structural stability [27]. This transformation from an irregular waste mass into a controlled geometry demonstrates how UAV-derived elevation data can be directly applied to define the final closure morphology. Based on the reprofiled landfill geometry, a drainage zoning and sewer network system was incorporated to control surface runoff and leachate conveyance across the landfill surface, as detailed in Figure S1.

The spatial distribution of excess waste thickness further guided the design of the final capping system, shown in Figure 8a. The proposed multilayer cover consists of a vegetative top layer, a drainage layer, and a low-permeability barrier, in accordance with established landfill design guidelines [28], while the detailed geotextile spreading and anchoring configuration is provided in Figure S2. Due to non-uniform structure of the curent condition, the thickness and extent of the cover are conceptually adapted to the spatial variability identified from the DSM, particularly in zones of significant elevation exceedance. This approach helps mitigate differential settlement and limits rainwater infiltration into the waste body.

A key component of the proposed rehabilitation strategy is the application of controlled leachate recirculation within the "green landfill" framework (Figure 6). As discussed in Section 3.2.2, the site's leachate is expected to have high concentrations of biodegradable organic matter. Instead of relying solely on external treatment, the design incorporates partial recirculation of leachate back into the landfill body to enhance moisture conditions and accelerate anaerobic degradation processes. This mechanism stabilizes organic waste and gradually reduces the pollutant load of the leachate, thereby lowering the treatment burden in subsequent stages. Such an approach is consistent with bioreactor landfill practices, which use leachate recirculation to improve waste degradation efficiency and reduce long-term environmental impacts.

Following this internal stabilization process, the remaining leachate is directed to an external treatment system, as illustrated in Figure 7. A leachate management system is proposed to mitigate potential environmental impacts, consisting of a multi-stage treatment system, including facultative ponds and constructed wetlands, tailored to the site's topography. The detailed configuration of the flow-directing aeration system and the constructed wetland treatment unit are further illustrated in Figure S3 and Figure S4, respectively. The facultative pond facilitates the reduction of organic load through combined aerobic and anaerobic processes. At the same time, the constructed wetland further removes nutrients and residual contaminants through plant uptake and microbial activity [29, 30]. This nature-based treatment configuration is particularly suitable for decentralized applications, offering lower operational costs and greater environmental compatibility than conventional treatment technologies.

In parallel, the modeled greenhouse gas emissions informed the integration of a passive gas management system within the capping structure, as shown in Figure 8a. The design incorporates vertical gas vents and permeable drainage layers to facilitate controlled gas release, thereby reducing internal pressure buildup and minimizing the risk of uncontrolled gas migration [26]. The passive gas venting network, including the arrangement of gas collection pipes and vertical vents within the capping system, is further detailed in Figure S5. Although the exact placement of vents requires further validation, their conceptual integration reflects the elevated methane generation potential associated with the observed overcapacity condition.

The integration of all rehabilitation components ... is summarized in Figure 8, where Figure 8a illustrates the key structural and environmental control components, while Figure 8b provides a three-dimensional representation of the final stabilized landfill configuration. Together, these figures demonstrate how UAV-derived spatial data can be translated into a coherent and site-specific closure strategy.

It should be emphasized that the proposed design remains at a conceptual level and has not yet undergone detailed geotechnical validation or cost optimization. Therefore, it should be interpreted as a preliminary engineering framework intended to support decision-making and guide further design development. Future work should incorporate subsurface investigations, stability analysis, and detailed engineering calculations to refine system performance.

Overall, this study highlights that UAV photogrammetry can serve not only as a high-resolution monitoring tool but also as a critical bridge between environmental assessment and engineering design. By explicitly linking site-specific spatial data with the configuration of closure components (Figure 6, Figure 7, and Figure 8), the proposed approach provides a practical and scalable pathway for landfill rehabilitation in data-scarce environments.

3.4 Limitations and Future Research

Despite the demonstrated advantages of UAV photogrammetry for high-resolution surface reconstruction and volumetric assessment, several limitations should be acknowledged in this study.

First, the UAV-derived DSM captures only surface morphology and does not provide information on subsurface conditions such as waste stratification, voids, or gas pathways. Consequently, the estimates of waste volume, GHG emissions, and leachate generation are subject to uncertainty and should be interpreted as first-order approximations.

Second, volumetric results depend on the reconstruction of the original landfill base. Any discrepancy between the assumed and actual base surface may introduce systematic errors in waste thickness and total volume estimation.

Third, the proposed closure design remains conceptual. Key aspects such as slope stability, settlement behavior, and system performance have not yet been validated through detailed geotechnical investigations or numerical modeling.

In addition, the application of the “green landfill” approach, particularly leachate recirculation, requires further site-specific validation to ensure effective control of moisture distribution and avoid potential instability risks. Future research should focus on integrating UAV data with subsurface investigation methods, long-term monitoring, and numerical modeling to improve the reliability of both environmental assessment and engineering design.

4. Conclusion

This study successfully demonstrated the application of UAV photogrammetry for landfill assessment and conceptual closure planning at the Da Mai landfill in northern Vietnam. High-resolution aerial imagery enabled detailed mapping, achieving a GSD of approximately 1.7 cm/pixel and a vertical RMSE of 5 cm. Based on the UAV-derived DSM, the total actual waste volume was estimated at 229,602 m^3, revealing that the landfill operated at overcapacity compared to its design limit, with peak elevations exceeding the authorized height by 1.5 m. Consequently, potential environmental risks were quantified, indicating substantial annual GHG emissions of 62,710 tCO_2e/year and leachate generation of 33,729 m^3/year. Rather than stopping at site monitoring, these UAV-derived parameters were directly utilized to formulate a conceptual closure design, sizing a nature-based leachate treatment sequence and passive gas venting. This integrated approach proves that UAV surveys can transition from descriptive monitoring to providing the hard quantitative baseline necessary for engineering closure designs in data-scarce regions.

Author Contributions

P.V.D: Conceptualization, Methodology, Data collection, Data analysis, Preparation of original manuscript and Editing of manuscript. L.T.B, P.V.T and H.T.D: Data analysis and Revising of manuscript. P.T.H: Editing of manuscript and Revising of manuscript.

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Competing Interests

The authors declare no conflict of interest regarding the publication of the paper.

AI-Assisted Technologies Statement

The authors used AI (Gemini) to improve their English writing skills, and we have thoroughly checked the content to ensure it accurately reflects the authors' intentions.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Figure S1: Drainage zoning and sewer structure.
2. Figure S2: Geotextile spreading and anchoring outline.
3. Figure S3: Layout of aeration waterfalls in a flow-directing aerated system.
4. Figure S4: Diagram of the constructed wetland.
5. Figure S5: Structure and arrangement of gas collection pipes.
6. Table S1: Coordinates of GCPs and Model.

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