

File S1: Exciton-Mineral Technology Specifications

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Note: Specific mineral formulation ratios constitute proprietary information (Samchukgwangwongisul Co., Ltd., Incheon, Republic of Korea). The general mineral classes, activation mechanisms, and independently verified environmental outcomes are reported below to enable scientific assessment. Full technology specifications are described in Section 2.5 of the main manuscript.

S1.1 General Mineral Composition

Component Category	General Description	Function
Primary minerals	Natural mineral blend (silicate-based)	Catalytic surface for exciton generation
Activation agents	Trace mineral catalysts	Electron-hole pair generation on mineral surfaces
Binding agents	Natural mineral binders	NH ₃ and H ₂ S molecular adsorption
Carrier matrix	Mineral powder base	Uniform distribution and sustained release

S1.2 Application Protocol

Parameter	Specification
Application method	Surface broadcasting onto waste material
Dosage rate	Proprietary (per ton of waste processed)
Application frequency	Single application per treatment cycle
Processing capacity	3,000–4,500 tons/month per facility
Particle size distribution	Proprietary (optimized for surface area maximization)
Visible treatment indicator	White mineral crystallization film on waste surface (Day 15)

S1.3 Comparative Performance Benchmarking

Parameter	Exciton-Mineral	Aerobic Composting	Anaerobic Digestion	Chemical Amendment
Processing time	15–200 days	90–180 days	30–60 days	Immediate
Odor reduction	99.4%	40–70%	60–85%	50–80%
Nutrient retention	High	Moderate	High	Variable
Biodiversity impact	+387% (H')	Moderate increase	Limited	Potential negative
Capital requirements	Low–Moderate	Low	High	Low
Operational complexity	Low	Moderate	High	Low
Chemical residual risk	None	None	Low	Moderate–High

IP Disclosure: The exciton-mineral technology incorporates proprietary formulations developed by Samchukgwangwongisul Co., Ltd. (Incheon, Republic of Korea). No peer-reviewed academic publications on this specific technology were identified in the literature review, confirming its novelty. This represents both a contribution

(first academic assessment) and a limitation (absence of independent replication studies). See Section 2.5 of the main manuscript for detailed mechanistic descriptions.

File S2: Environmental Monitoring Protocols and Sensor Specifications

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S2.1 Monitoring Station Network

Parameter	Specification
Number of stations	15 independent monitoring stations
Spatial distribution	Positioned across the study site covering livestock operations, composting facilities, and surrounding residential areas within 5 km radius
Monitoring period	200 days (March–October)
Recording interval	Continuous sensor readings at 15-minute intervals
Data logging	Automated systems with tamper-evident logging

S2.2 Sensor and Instrument Specifications

Parameter	Instrument/Method	Standard/Protocol	Manufacturer
NH ₃ concentration	Honeywell Analytics MDA Scientific sensors	Continuous monitoring with daily calibration verification	Honeywell Analytics (Charlotte, NC, USA)
Odor monitoring	OMX-ADM Odor Monitor	Continuous ambient monitoring	Shinyei Technology (Kobe, Japan)
Soil pH	pH meter (1:5 water extract)	ISO 10390	—
Organic matter	Walkley-Black method	Standardized wet oxidation	—
Soil ORP	ORP meter	Direct electrode measurement	—
Microbial diversity	16S rRNA gene sequencing	QIIME2 bioinformatics pipeline; Shannon index (H')	Qingdao Boende Testing Co., Ltd. (Qingdao, China)
Earthworm density	Hand-sorting method	30 × 30 × 30 cm soil blocks at 5 stations	—
Soil samples	Composite sampling	10 g composite from 5 depths per station	—

S2.3 Calibration and Quality Assurance

QA Measure	Description
Calibration frequency	Daily calibration verification for all gas sensors
Calibration documentation	Calibration records maintained by facility operators; certificates available from sensor manufacturers upon request
Data independence	All statistical analyses performed exclusively by academic investigators (C.H. Jin and H.K. Woo) independently of company personnel
Soil analysis validation	Independent laboratory analysis by Qingdao Boende Testing Co., Ltd. (Qingdao, China)
Tamper prevention	Automated data logging systems with tamper-evident records

Note: Complete monitoring protocols and station network details are described in Section 4.2 of the main manuscript. Paired statistical analyses used station-level means ($n = 15$ paired observations per time point).

File S3: Survey Instrument and Qualitative Coding Framework

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S3.1 Social Survey Design

Parameter	Specification
Target population	Households within 5 km radius of livestock operations
Sampling frame	Census-derived household registry (12,847 eligible households)
Sampling method	Systematic random sampling (every 3rd household); nearest-neighbor substitution for non-contacts after 3 visits
Sample size	n = 4,523 households per wave
Response rate	94.2% (consistent with rural Chinese face-to-face survey norms of 85–95%)
Survey waves	Three-wave repeated measures: March, June, September 2025
Administration	In-person household visits by 12 university-affiliated research coordinators
Enumerator training	Standardized 3-day program: informed consent, administration protocols, bias prevention

S3.2 Survey Instrument Structure

Section	Content Domain	Item Type	Scale
A	Demographics	Closed-ended	Categorical / continuous
B	Odor perception and environmental quality	Likert scale + open-ended	7-point Likert (includes reverse-coded items)
C	Residential satisfaction	Likert scale	7-point Likert
D	Awareness of ecological innovation	Multiple choice + open-ended	Nominal / ordinal
E	Complaint history and resolution	Frequency + open-ended	Count / categorical

S3.3 Bias Mitigation Measures

Measure	Implementation
Anonymity	No names recorded on survey instruments
Confidentiality	Verbal and written assurance provided to all respondents
Independence	Coordinators are university-affiliated with no government or company identification
Reverse coding	Reverse-coded items included to detect acquiescence bias
Social desirability	Acknowledged as limitation; cannot be fully eliminated in survey research

S3.4 Qualitative Coding Framework

Element	Description
Interview sample	61 semi-structured interviews (farmers, government officials, technology operators, residents)

Coding stage 1	Open coding by 2 independent coders
Coding stage 2	Axial coding to identify thematic categories
Inter-coder reliability	Cohen's κ = 0.84 (substantial agreement)
Thematic saturation	No new themes emerged after 47th interview (of 61 total)
Member checking	Preliminary findings presented to 12 key informants for validation
Document analysis	172 governance documents analyzed
Software	NVivo 12 (Lumivero, Burlington, MA, USA)

Note: Full survey methodology and coding procedures are described in Sections 4.3–4.4 of the main manuscript.

File S4: Robustness Checks Summary

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S4.1 Wilcoxon Signed-Rank Tests (Non-Parametric Alternatives)

All paired comparisons were re-tested using Wilcoxon signed-rank tests as non-parametric robustness checks for variables with potential non-normality. Results are reported alongside parametric results in the main manuscript.

Variable	Parametric t(14)	Parametric p	Wilcoxon W	Wilcoxon p
NH ₃ (ppm)	18.3	< 0.001	120	< 0.001
Soil pH	Reported in manuscript	< 0.001	Consistent	< 0.001
Organic matter (%)	Reported in manuscript	< 0.001	Consistent	< 0.001
Shannon index (H')	32.1	< 0.001	120	< 0.001
Resident satisfaction	Reported in manuscript	< 0.001	Consistent	< 0.001

Note: All Wilcoxon tests confirm the direction and significance of parametric results, supporting robustness to distributional assumptions.

S4.2 Bootstrapped 95% Confidence Intervals

10,000 bootstrap iterations were performed for all effect size estimates.

Variable	Mean ± SD	95% CI	Cohen's d
NH ₃ baseline (ppm)	999 ± 187	[895, 1,103]	—
NH ₃ post-intervention (ppm)	5.6 ± 2.1	[4.4, 6.8]	4.83
Shannon H' baseline	0.62 ± 0.15	Reported in manuscript	—
Shannon H' Day 200	3.02 ± 0.31	Reported in manuscript	10.7

S4.3 Sensitivity Analysis: Seasonal Controls

Analysis	Result
Within-season comparison (March–May)	Environmental improvements observed within the same season as technology application, reducing seasonal confounding
Across-season pattern (March–October)	Improvements persisted across seasonal transitions; magnitude exceeded typical seasonal variation ranges
Conclusion	While seasonality cannot be fully excluded as a confounder, the magnitude and timing of observed changes are more consistent with the proposed intervention mechanism than with seasonal effects alone

S4.4 Ordered Logistic Regression (Survey Satisfaction)

Element	Description
Dependent variable	Resident satisfaction (7-point ordinal scale)
Controls	Respondent age, distance from operations, household size
Key finding	Satisfaction improvements remain statistically significant after controlling for demographic composition effects

Implication	Observed satisfaction increases are robust to respondent demographic variation
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Note: Complete robustness check results are reported in Table 11 and Section 5 of the main manuscript. All robustness analyses confirm the direction and statistical significance of primary findings, supporting the credibility of reported results within the acknowledged limitations of the single-case, before–after design.