



From Brewing Waste to Bio-Resource: A Strategic Up-Cycling for Regenerative Agriculture in the Circular Economy

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Abstract

The brewing industry generates substantial volumes of Brewer's Spent Yeast (BSY), accounting for approximately 15% of total brewery by-products and contributing an estimated 2–4% of total production costs through disposal and handling. In Thailand, where beer production reached 2.3 billion liters in 2024, BSY remains predominantly managed under a linear "take–make–dispose" model, leading to economic inefficiencies and methane emissions from landfill practices. This study proposes a Cascading Utilization Model to reposition BSY from an industrial liability into a high-value bio-input for regenerative agriculture. Using methodological triangulation that integrates industrial production data with biochemical profiling from existing literature, the research identifies agricultural upcycling as the most economically and technically viable valorization pathway, thereby avoiding the costly RNA-reduction and debittering processes required for food-grade applications. The analysis confirms that BSY's high protein content (45–60%) and peptide-rich fractions possess functional properties associated with enhanced plant nutrient uptake and root development, indicating potential improvements in nutrient use efficiency (NUE). By diverting BSY from disposal to agricultural deployment, breweries may reduce waste-handling costs while substantially reducing landfill dependence for this biomass. For the agricultural sector, the model suggests a locally sourced alternative to volatile synthetic fertilizers, with potential for cost stabilization through reduced processing complexity and improved agronomic efficiency. The study further highlights the importance of regulatory standardization to support safe integration of industrial by-products into Thailand's agricultural supply chain. Strategically aligned with Thailand's Bio-Circular-Green (BCG) Economy Model, the proposed framework establishes a scalable pathway for industrial symbiosis between breweries and farmers, advancing circular bioeconomy practices.

Keywords: *bio-resource, brewing, waste, up-cycling, regenerative agriculture, circular economy*

1. Introduction

The global brewing industry is a major consumer of agricultural raw materials such as malts, yeast, hops, as well as freshwater resources. While the sector generates substantial economic value, it concurrently produces significant environmental burdens through its waste streams. In Thailand, the beer market reached 2.3 billion liters in 2024 (Euromonitor International, 2025), a scale of output that intensifies waste management pressures within the country's 2026 economic and regulatory landscape. As industrial expansion outpaces sustainable disposal infrastructure, the growing volume of beer production by-products poses increasing challenges to operational efficiency and environmental compliance.

One of the major by-products of the brewing process is Brewer's Spent Yeast (BSY), which is the second-largest by-product and accounts for approximately 15% of total brewery waste, exceeding 400,000 metric tons annually worldwide (Chattaraj et al., 2024; Demirgul et al., 2022; Jaeger et al., 2020; Zeko-Pivač et al., 2022). Under the prevailing linear "take-make-dispose" model (Chattaraj et al., 2024; Mitri et al., 2022; Zeko-Pivač et al., 2022), BSY is predominantly directed toward low-value pathways such as animal feed, landfilling, or conventional composting (Scharff et al., 2024; Russ & Meyer-Pittroff, 2004). These approaches are economically inefficient, with waste handling costs estimated at 2–4% of total beer production expenses due to dehydration, transport, and treatment (Jaeger et al., 2020).

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Biochemical profiling indicates that this disposal-oriented model results in the loss of a nutrient-dense resource. On a dry weight basis, BSY contains 45–60% protein, essential amino acids, B vitamins, minerals such as potassium (K) and phosphorus (P), and bioactive compounds, including β -glucans (Avramia & Amariei, 2021; Zeko-Pivač et al., 2023). Although food-grade applications exist, their scalability is constrained by technical barriers, particularly the high RNA content and the need for debittering processes to meet safety standards (Jaeger et al., 2020; Zeko-Pivač et al., 2023). These requirements increase processing complexity and limit economic feasibility for large-scale valorization.

Agriculture thus emerges as a strategically viable alternative. However, existing applications remain largely confined (Chattaraj et al., 2024; Ciobanu et al., 2024; Jaeger et al., 2020). Such passive approaches primarily return organic matter to the soil but do not optimize the functional bioactive components embedded within yeast biomass. To address this innovation gap, this study proposes a transition from simple composting to functional transformation, a process that deliberately upgrades BSY into peptide-rich bio-inputs. Unlike unprocessed compost, functionally transformed BSY enhances the availability of bioactive peptides capable of stimulating root development and improving nutrient uptake efficiency. This approach aims to resolve the structural mismatch in the Thai bio-economy, where a biochemically rich industrial by-product remains underutilized, while the agricultural sector faces rising synthetic fertilizer costs and environmental degradation.

2. Objectives

This study aims to address the innovation gap in brewery waste management through the following specific objectives:

- 1) To assess the socio-economic and environmental impacts of linear waste management models for BSY within the Thai brewing industry, focusing on disposal costs and carbon footprint.
- 2) To evaluate the biochemical feasibility of Brewer's Spent Yeast (BSY) as a high-value agricultural bio-input, in comparison with the technical constraints and processing requirements of food-grade applications.
- 3) To conceptualize a "Cascading Utilization Model" that systematically structures BSY valorization toward agricultural bio-input production.
- 4) To analyze the strategic alignment of BSY valorization with Thailand's Bio-Circular-Green (BCG) Economy Model and to evaluate its implications for industrial and agricultural stakeholders.

3. Materials and Methods

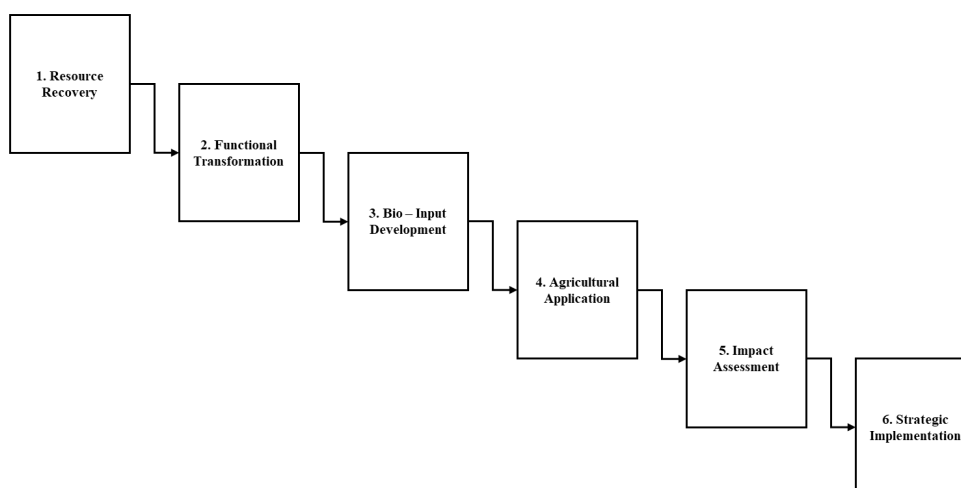
This study employs a methodological triangulation approach, integrating secondary industrial data, biochemical profiling derived from existing literature, and innovation and policy analysis frameworks. The triangulation ensures analytical robustness by combining quantitative evidence, biochemical feasibility assessment, and strategic evaluation.

To address the complexity of transitioning from a linear waste model to a circular bioeconomy, this study developed the Integrated Conceptual Framework for BSY Valorization and Strategic Evaluation (Figure 1). As illustrated, the methodology operates under two overarching themes, Industrial and Environmental Assessment Foundation and Policy Alignment and Circular Economy Integration, and is structured into three distinct phases encompassing six sequential steps as follows:



Integrated Conceptual Framework for BSY Valorization and Strategic Evaluation

Industrial & Environmental Assessment Foundation



Policy Alignment & Circular Economy Integration

Figure 1 Integrated conceptual framework illustrating the structured progression from industrial and environmental assessment to BSY valorization, agricultural application, impact evaluation, and strategic implementation within a circular bioeconomy context

The triangulation approach enhances validity by cross-verifying industrial economic indicators, biochemical composition data, and policy-based strategic analyses to ensure methodological coherence across technical and systemic dimensions.

Phase 1: Industrial & Environmental Assessment Foundation

The first phase establishes a baseline understanding of BSY as an underutilized industrial by-product by synthesizing quantitative and qualitative data. This foundation informs the subsequent operational steps.

- **Data Sourcing:** Secondary data on beer production volume, industrial waste volumes, BSY generation, and waste management costs were collected from global brewing reports and Thai market analyses. Euromonitor International (2025) reported approximately 2.3 billion liters of beer production in Thailand, which were used to estimate BSY generation and waste implications.
- **Biochemical Profiling:** The biochemical characteristics of BSY were established by aggregating data from proximate analyses. The study utilizes established values for protein content (45–60%), amino acid profiles, and β -glucan levels (Avramia & Amariei, 2021; Tao et al., 2022). This synthesis is used to determine the baseline value potential of BSY as a bio-input.

Phase 2: The Cascading Utilization Model (Steps 1–4)

To address the innovation gap in BSY waste management, the study constructs a structured operational pathway that prioritizes high-value use over disposal. This phase maps directly to Steps 1 through 4 of the integrated framework.

- **Step 1 Resource Recovery:** Identifying early separation and stabilization protocols to capture BSY at the brewery level before degradation occurs.
- **Step 2 Functional Transformation:** Evaluating environmentally compatible processing methods to upgrade raw BSY, focusing on increasing the availability of bioactive peptides and amino acids without the need for the complex RNA-reduction required in food-grade processing.

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- **Step 3 Bio-Input Development:** Structuring the formulation of the transformed biomass into a stabilized, standardized bio-input tailored for practical agricultural deployment.
- **Step 4 Agricultural Application:** Analyzing the analytical modeling of the developed bio-inputs in crops, focusing on qualitative criteria such as nutrient use efficiency (NUE), processing complexity, and scalability. The Technology Readiness Level (TRL) framework was utilized to assess the feasibility and maturity of the pathway (Pasquet et al., 2024).

Phase 3: Strategic Evaluation and Policy Integration (Steps 5–6)

The final phase evaluates the adoption feasibility, sustainability relevance, and macroeconomic alignment of the proposed valorization model, corresponding to Steps 5 and 6 of the framework and guided by the theme of Policy Alignment and Circular Economy Integration.

- **Step 5. Impact Assessment:** The study assesses the environmental and end-user impacts of the model. To evaluate stakeholder adoption, Rogers' Diffusion of Innovations theory is applied to analyze the "Relative Advantage" of BSY-derived inputs against conventional chemical fertilizers (Kostecki & Greinert, 2024; Terefe et al., 2023). Furthermore, a sustainability assessment aligns the model's impact with the United Nations Sustainable Development Goals (SDGs), specifically Goal 12 (Responsible Consumption) and Goal 13 (Climate Action) (United Nations, 2025).
- **Step 6. Strategic Implementation:** The proposed strategy is mapped to the indicators of Thailand's Bio-Circular-Green (BCG) Economy Model. This step evaluates the implementation readiness across three key dimensions: Bio-economy (resource efficiency), Circular Economy (waste reduction), and Green Economy (environmental impact mitigation) to foster industrial symbiosis (National Science and Technology Development Agency (NSTDA), 2025; United Nations, 2025).

This structured methodological design enables a comprehensive evaluation of BSY valorization across technical feasibility, agronomic applicability, environmental performance, and strategic implementation dimensions.

4. Results and Discussion

This section integrates quantitative evidence on industrial waste generation with a qualitative evaluation of biochemical feasibility and strategic management frameworks. By synthesizing industrial data and existing biochemical literature, the study repositions BSY from an industrial liability to a potential agricultural resource.

4.1 Quantitative Analysis of Industrial Inefficiency: The Cost of the Linear Model

The analysis of global and regional production data indicates that the current management of BSY represents a significant economic and environmental inefficiency (Scharff et al., 2024; Russ & Meyer-Pittroff, 2004). Global data indicates that BSY accounts for approximately 15% of total solid by-products generated by the brewing industry (Zeko-Pivač et al., 2023). Thailand's beer industry generates tens of thousands of tons of this biomass annually (Euromonitor International, 2025; Jaeger et al., 2020). Historically, this material has been managed via a linear "take-make-dispose" model, where it is treated primarily as a waste stream rather than a recoverable resource (Mortero et al., 2024; Pasquet et al., 2024). The study finds that disposal methods, primarily landfilling or low-value feed sales, fail to offset the high handling costs (Chattaraj et al., 2024; Demirgul et al., 2022). Previous studies indicated that these waste streams account for 2–4% of total beer production costs (Chattaraj et al., 2024; Kerby & Vriesekoop, 2017; Zeko-Pivač et al., 2023).

These findings highlight a structural inefficiency in current brewery waste systems. While Brewer's Spent Grain (BSG) has achieved relatively full resource recovery, BSY remains a substantial disposal challenge, with a high carbon footprint due to methane emissions from anaerobic decomposition in landfills (Scharff et al., 2024). Based on Thailand's 2024 beer production volume (2.3 billion liters) and the estimated



15% contribution of BSY to total by-products, the national waste stream represents a substantial recoverable biomass pool with direct economic implications for cost mitigation.

4.2 Biochemical Feasibility: The "Food vs. Agriculture" Dilemma

A review of the biochemical profile of BSY reveals a distinct advantage for agricultural applications over human food applications. The analysis confirms that BSY is nutrient-dense, containing 45–60% protein on a dry weight basis, with essential minerals like Potassium (K), Magnesium (Mg), and Zinc (Zn) (Demirgul et al., 2022; Puligundla et al., 2020). When converted into amino acids and short-chain peptides, these protein fractions are reported to contribute to plant physiological functions beyond basic nutrition. The literature indicates that amino acids and peptide fractions derived from yeast biomass can act as bioactive signaling compounds, stimulating root elongation and lateral root development (Vargas et al., 2024). Specific amino acids found in BSY, such as glutamic and aspartic acid (Tao et al., 2022), function as natural chelating agents. These amino acids form organic complexes with micronutrients (e.g., Fe, Zn, Mn), significantly increasing their bioavailability and transport efficiency within the plant system (Vargas et al., 2024).

It is also rich in cell wall polysaccharides, specifically β -glucans and mannoproteins, which are known immunostimulants (Mirzaei et al., 2021). A critical pain point identified is the high content of nucleic acids (RNA), ranging from 6–15% (Mirzaei et al., 2021; Rodriguez et al., 2023; Tao et al., 2022). In human food applications, this is a limiting factor because high RNA intake can elevate uric acid levels, leading to health risks like gout (Mirzaei et al., 2021). However, this study identifies agriculture as the path of least resistance for BSY valorization. Unlike humans, plants do not require RNA removal; the degradation of RNA releases nucleotides that serve as sources of phosphorus and nitrogen. Therefore, transforming BSY into a plant bio input avoids the expensive processing required for food-grade yeast (such as debittering and RNA reduction), making the agricultural route technically and economically superior (Jaeger et al., 2020; Zeko-Pivač et al., 2022).

Table 1 synthesizes key industrial and biochemical indicators supporting the prioritization of agricultural valorization over disposal-oriented pathways.

Table 1 Quantitative and Biochemical Profile of BSY Supporting Agricultural Valorization

Parameter	Value Range	Strategic Implication for Valorization	Reference Sources
BSY Share of By-Products	~15% of total brewery solid waste	Represents a high-volume liability under linear models; strong scalability potential for recovery.	(Zeko-Pivač et al., 2023)
Waste Management Cost	2–4% of total production costs	Creates a direct economic incentive for breweries to divert BSY from landfills to value-added pathways.	(Jaeger et al., 2020)
Protein Content	45–60% (dry weight basis)	Serves as a nutrient-dense base for generating functional amino acids and bioactive peptides.	(Demirgul et al., 2022; Puligundla et al., 2020)
Nucleic (RNA) Content	6–15%	Acts as a barrier to human food applications (due to gout risk) but serves as a highly beneficial phosphorus and nitrogen source for plants.	(Mirzaei et al., 2021; Tao et al., 2022)
Functional Amino Acids	High in glutamic and aspartic acid	Functions as natural chelating agents, significantly increasing the bioavailability and transport of micronutrients (Fe, Zn, Mn) in plants.	(Tao et al., 2022; Vargas et al., 2024)
Cell Wall Polysaccharides	Rich in β -glucans and mannoproteins	Acts as known immunostimulants to support plant stress resilience.	(Mirzaei et al., 2021)



4.3 Proposed Strategic Solution: The Cascading Utilization Model

The convergence of industrial inefficiency and biochemical potential provides an analytical basis for the proposed valorization pathway. To address the identified innovation gap in brewery waste management, this study proposes the "Cascading Utilization Model" for BSY. This model prioritizes the sequential extraction of value rather than disposal, aligning with circular economy principles described in the literature (Zeko-Pivač et al., 2023).

Table 2 Strategic Framework for the Cascading Utilization of BSY

Stage	Objective	Conceptual Approach	Rationale	Indicative Outcome
Stage 1: Resource Recovery	Early separation and stabilization of BSY within brewery operations	BSY has high moisture content and degrades rapidly if unmanaged (Olivares-Galván et al., 2022).	Early recovery prevents spoilage and preserves functional biomass quality as reported in the literature (Zeko-Pivač et al., 2023).	BSY maintained as a stabilized secondary resource rather than a disposal burden.
Stage 2: Functional Transformation	Environmentally compatible enhancement of functional availability	Prior studies indicate that yeast biomass can be upgraded to increase peptides and amino acids without requiring complex RNA-reduction processes (Ciobanu et al., 2024)	Transforming BSY unlocks natural chelating agents and immunostimulants trapped in the biomass. (Vargas et al., 2024).	Upgraded biomass with highly available peptides, amino acids, and minerals.
Stage 3: Bio-Input Development	Structuring the formulation of the transformed biomass	Creating a stabilized, standardized bio-input tailored for practical deployment.	Ensures the agricultural input is consistent, scalable, and compatible with existing farming practices.	A market-ready, peptide-rich bio-input formulation.
Stage 4: Agricultural Application	Regenerative deployment of bio-inputs for crops	Literature reports that peptide-rich bio-inputs can support plant physiological functions, including nutrient uptake efficiency and stress tolerance. (Zeko-Pivač et al., 2023)	Specific applications have demonstrated significant benefits for horticultural seedlings (Vargas et al., 2024) and for urban forestry crops such as silver maple (Sifton et al., 2023).	Relative advantage over conventional synthetic inputs in terms of Nutrient Use Efficiency (NUE) and crop quality.

Table 2 illustrates how the "Cascading Utilization Model" operationalizes the shift from linear waste disposal to circular value creation through three distinct stages. Stage 1 (Resource Recovery) addresses the critical logistical challenge of BSY by emphasizing early segregation and stabilization. This step mitigates rapid degradation and preserves the functional potential of the biomass for subsequent utilization pathways (Vargas et al., 2024; Zeko-Pivač et al., 2023). Stage 2 (Functional Transformation) focuses on upgrading BSY into biologically functional inputs using environmentally compatible approaches as reported in existing studies. The model emphasizes functional outcomes, specifically the availability of peptide-based and nutrient-rich components relevant for plant systems (Ciobanu et al., 2024). Stage 3 (Bio-Input Development) ensures formulation stability, standardization, and compatibility with existing agricultural practices, thereby enabling scalability and practical deployment. Finally, Stage 4 (Agricultural Application) validates the pathway for BSY valorization. The study indicates that peptide-rich inputs can enhance Nutrient Use

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Efficiency (NUE) and crop performance, supporting the concept of “relative advantage” as defined in diffusion of innovation theory (Kostecki & Greinert, 2024).

Hence, the proposed model demonstrates how BSY, an industrial by-product, can be transformed into value-creating inputs within regenerative agricultural systems.

4.4 Strategic Alignment with the BCG Economy and SDGs

The proposed Cascading Utilization Model demonstrates strong alignment with Thailand’s Bio-Circular-Green (BCG) Economy Model and the UN Sustainable Development Goals (SDGs), focusing on biological resource efficiency, circular material flows, and environmental impact reduction (National Science and Technology Development Agency (NSTDA), 2025). The transition from landfilling to bio-input production supports the circular economy pillar by returning industrial resources to the agricultural sector and implementing a “cascading utilization” approach that extends resource lifecycles (Zeko-Pivač et al., 2023). It further addresses the bio-economy and green economy pillars by converting low-value by-products into functional bio-inputs while reducing landfill use, which is associated with greenhouse gas emissions (Demirgul et al., 2022; Kostecki & Greinert, 2024). To fully operationalize this BCG alignment, Thai regulators should implement specific policy frameworks, such as establishing standardized quality and safety certifications for bio-inputs derived from industrial brewery waste. Implementing these standards would ensure consistent agronomic efficacy, build end-user trust, and formally integrate upcycled secondary materials into the national agricultural supply chain.

From a diffusion of innovation perspective, the study suggests that the adoption potential of BSY-derived bio-inputs is linked to relative advantage and shared value for both breweries and farmers (Carley & Yahng, 2018). For breweries, the strategy offers a pathway to reduce waste-handling costs, which currently account for 2–4% of production expenses (Jaeger et al., 2020), while promoting corporate social responsibility (CSR) initiatives. For the agricultural sector, the framework emphasizes opportunities for farmers to access high-performance organic inputs that restore soil health, directly addressing the critical need for sustainable alternatives to rising synthetic fertilizer costs. Because the agricultural valorization pathway bypasses the expensive debittering and RNA-reduction processes required for human food applications, manufacturing complexity and associated processing costs are structurally reduced. This cost-efficiency suggests the potential for competitive pricing relative to synthetic fertilizers, indicating their potential as an affordable and functional alternative for Thai farmers who are currently burdened by soil degradation and the rising costs of conventional chemical inputs. Compared with synthetic fertilizers, which are subject to volatile global price fluctuations and import dependency, BSY-derived bio-inputs represent a locally sourced alternative with lower embedded processing complexity. Amino acid-based inputs are typically applied at lower dosages than conventional nitrogen fertilizers, potentially reducing total input volumes while improving nutrient use efficiency (NUE). This suggests that farmers may benefit not only from environmental advantages but also from more stable input costs and improved return on investment over time.

The outcomes directly support SDG 12 (Responsible Consumption and Production) by minimizing industrial waste and SDG 13 (Climate Action) by mitigating methane emissions from anaerobic decomposition, while also strengthening agricultural supply chain resilience and fostering regenerative industrial practices (United Nations, 2025). These standards may include specifications for nutrient composition, microbial safety, heavy metal limits, and labeling requirements. A formal regulatory framework would reduce market uncertainty, enhance farmer trust, and accelerate the adoption of industrial-agricultural symbiosis under the BCG strategy.

Additionally, fiscal incentives or pilot demonstration programs could be introduced to encourage brewery–farmer partnerships in regional agricultural clusters.

5. Conclusion

This study concludes that Brewer’s Spent Yeast (BSY) should be reconsidered not as a residual waste stream, but as an underutilized industrial by-product. While the Thai brewing industry generates tens of thousands of tons of BSY annually, current management strategies remain largely disposal-oriented,



resulting in economic inefficiencies and environmental burdens. Through the development of the Cascading Utilization Model, this research determines that the most viable valorization pathway is not human food, but regenerative agriculture. The biochemical analysis confirms that BSY is nutrient-dense and rich in bioactive compounds. However, the high nucleic acid (RNA) content presents a major obstacle to the food market due to associated health risks. In contrast, this characteristic becomes a relative advantage in agricultural systems, where RNA degradation products can be utilized as nutrient sources.

The proposed Cascading Utilization Model structures findings into a four-stage strategic framework comprising Resource Recovery, Functional Transformation, Bio-Input Development, and Agricultural Application. By repositioning BSY as a raw material rather than a disposal burden, the framework highlights opportunities to generate bio-inputs rich in bioactive peptides and essential minerals. Existing literature suggests that such inputs could enhance Nutrient Use Efficiency (NUE) and stress tolerance in crops, offering a sustainable alternative to synthetic applications.

The adoption of this model offers significant shared value, aligning with Thailand's Bio-Circular-Green (BCG) Economy Model by promoting resource efficiency, circular material flows, and environmental impact mitigation. For breweries, it is possible to shift from a "take-make-dispose" model to a value-oriented pathway, thereby offering opportunities to reduce waste management costs and greenhouse gas emissions associated with landfilling. For the agricultural sector, the framework emphasizes opportunities for farmers to access potentially affordable, high-performance organic inputs that restore soil health, addressing the critical need for sustainable alternatives in response to rising fertilizer costs.

Future research should focus on a pilot-scale validation to translate the conceptual framework to empirical field trials on specific crops, particularly measuring yield and crop performance levels. Additionally, a comprehensive Life Cycle Assessment (LCA) should be conducted to quantify the exact carbon reduction achieved by diverting BSY from landfills to agricultural application. Overall, this study provides a strategic foundation, demonstrating that BSY valorization for regenerative agriculture is technically feasible, economically promising, and environmentally aligned with long-term sustainability goals.

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