European Journal of Sustainable Development (2025), **14**, 4, 39-50 ISSN: 2239-5938
Doi: 10.14207/ejsd.2025.v14n4p39

Circular Business Models for Composting Waste Seaweed: Potential, Barriers, and Enablers

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ABSTRACT:
This study examines circular business models for transforming beach-cast seaweed waste into high-value agricultural products within municipal contexts. We systematically reviewed 53 peer-reviewed publications (2017-2024) to analyze how coastal municipalities can convert problematic seaweed accumulations into revenue-generating compost and soil amendments. Our findings reveal that while implementation faces barriers including supply unpredictability, heavy metal contamination concerns, and regulatory constraints, these challenges are counterbalanced by rising fertilizer costs and growing policy support for circular bioeconomy initiatives. We propose four scalable business models, particularly on municipal service integration, which transform waste management costs into potential revenue streams while addressing how municipalities can operationalize circular bioeconomy principles through concrete, implementable strategies. Success requires coordinated intervention across technology, supply chain design, and regulatory frameworks.

Keywords: Circular Bioeconomy; Seaweed Valorization; Municipal Business Models; Waste-to-Resource

1. Introduction

Coastal municipalities worldwide face an increasingly urgent challenge: managing the growing volumes of seaweed washing ashore due to climate change and ocean warming. The conventional procedure involves collecting seaweed and subsequently hauling it away for disposal. This represents the kind of linear thinking that circular economy advocates have spent decades trying to change. While circular economy principles advocate transforming waste into resources, most municipalities continue to follow linear approaches for beach wrack, or beach cast (naturally deposited seaweed).

Climate change, ocean warming, and anthropogenic nutrient inputs have intensified seaweed blooms, creating substantial shoreline deposits that generate odor issues, health concerns, tourism impacts, and costly removal operations (Miranda et al., 2021). Seaweed management has become a year-round problem for a myriad of coastal communities rather than a seasonal inconvenience.

The circular bioeconomy (CBE) offers municipalities an alternative framework that reconceptualizes seaweed waste as feedstock for high-value agricultural products. As Salvador et al. (2021) define it, the CBE employs biomass to manufacture value-added products while maximizing value over extended periods. Within this framework,

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problematic seaweed accumulations become inputs for valuable compost and soil amendments.

However, there is an implementation gap. Despite well-established scientific understanding of seaweed's agricultural benefits and growing policy interest in circular approaches, very few municipalities have successfully operationalized these concepts. The Solrød Municipality case demonstrates successful integration of 90% of cast seaweed from 3.7 km coastline into renewable energy and fertilizer production while achieving 32,800 tons annual CO_2 emission reduction (Lybæk & Kjær, 2023). However, this success required addressing critical technical bottlenecks, particularly sand separation technology crucial for economic viability, where cyclone separation reduced sand content from 60-90% to manageable levels of 10-20% (Lybæk & Kjær, 2023). The limited standardization in processing workflows and quality assessment methods across the broader literature suggests that replicating such success requires context-specific technical solutions rather than standardized approaches (Salvador et al., 2025). The literature is rich with technical possibilities but thin on practical business models that can survive the realities of municipal budgets, procurement processes, and political cycles, and critically, the quality control requirements necessary for safe agricultural application.

This paper addresses municipal implementation specifically because municipalities face unique constraints and opportunities. Unlike private enterprises, they must balance environmental objectives with fiscal responsibility to taxpayers. They operate within regulatory frameworks that can both enable and constrain innovation. Most importantly, they manage the beach cleaning operations that generate the raw material, making them natural integrators of the entire value chain.

Our problem identification draws from both our previous literature review (Salvador et al., 2025) and responses from a PowerBio project workshop we conducted at Gate21 in Albertslund, Denmark, on April 2, 2025. Gate 21 is a partnership for municipalities, regions, businesses, and knowledge institutions that works toward climate action. The workshop participants, the majority of whom are key decision makers in municipalities, filled out a questionnaire individually and a Business Model Canvas (Osterwalder & Pigneur, 2010) in a group session. This combined input guides our analysis to a central question: How can coastal municipalities transform problematic seaweed waste from an expense into a revenue opportunity while meeting environmental and public service objectives? We examine this through four key research areas:

1. High-value agricultural applications suitable for municipal production scales
2. Municipal-specific barriers and enablers for seaweed composting
3. Business models optimized for municipal contexts and capabilities
4. Strategic recommendations for municipal implementation

2. The Value Proposition

Successful implementation enables municipalities to transform waste management expenses into potential revenue sources while demonstrating environmental leadership and supporting local agricultural sectors. More fundamentally, it represents a shift from being a cost center to becoming a value creator, precisely the kind of transformation that makes CBE principles tangible rather than abstract.

3. Research Methodology

This study is based on a systematic literature review following the PRISMA framework, searching major databases (Web of Science, Scopus, Science Direct) for peer-reviewed publications, published between 2017 and 2024, focusing on the potential of converting seaweed wrack into high-value products (Salvador et al., 2025). Articles that focus on cultivated seaweed were not included, as we want to address waste seaweed sources.

The 2017-2024 period captures the evolution from early circular economy enthusiasm to more mature, implementation-focused research. This timeframe also coincides with significant policy developments, including the EU Circular Economy Action Plan and growing municipal experience with circular initiatives.

We adapted the Triple Bottom Line Business Model Canvas (Joyce & Paquin, 2016), which expands upon the Business Model Canvas framework (Osterwalder & Pigneur, 2010) to incorporate an environmental layer based on a lifecycle perspective and a social layer based on a stakeholder perspective. This adaptation was necessary because traditional business model frameworks do not adequately address the multi-stakeholder, public-benefit considerations that characterize municipal operations.

To identify the most pertinent literature, Scite.ai (scite, 2024) from the DTU library was consulted. Claude (Anthropic, 2024) was used as a research assistant. All AI-generated content was reviewed and verified by the authors.

Our analysis shows that municipal seaweed valorization shows interesting commercial potential for three product categories: premium biofertilizers, soil enhancement products, and growing media substitutes. These applications emerged not only from technical feasibility assessments but also from our Gate21 workshop discussions with municipal decision-makers, who emphasized the need for products that could justify initial infrastructure investments while aligning with existing municipal capabilities. The following section examines each application's market potential, technical requirements, and strategic positioning for municipal implementation.

4. High-Value Applications: Premium Biofertilizers

Seaweed waste provides balanced macro- and microelements, particularly potassium, calcium, and trace minerals, enhancing plant nutrient uptake while minimizing leaching risks associated with synthetic fertilizers (Karthik & Jayashri, 2023). Portuguese and Irish municipalities have demonstrated notable yield improvements when seaweed-derived fertilizers are applied, with some operations achieving price premiums of 2-3x over conventional compost (Pardilhó et al., 2023; Tedesco & Stokes, 2017).

A critical consideration for municipal seaweed valorization is the management of heavy metal contamination. Research demonstrates that seaweed can accumulate heavy metals from marine environments, particularly cadmium, which can restrict the use of seaweed-derived digestate as fertilizer (Lybæk & Kjær, 2023).

The nutritional composition varies by species, with brown algae generally containing higher concentrations of beneficial compounds (Silva et al., 2024; Pinteus et al., 2018). This variability is not necessarily a problem, but rather an opportunity for product specialization. Municipalities can develop signature fertilizer blends based on their local seaweed characteristics and regional agricultural needs.

This application may require partnerships with research institutions or private companies to provide technical expertise for product development and contamination management, while municipalities contribute raw material and processing capacity.

4.1 Soil Enhancement Products

Seaweed-derived composts significantly improve soil physical properties, particularly water retention capacity and aeration (Pardilhó et al., 2023). The high fiber content and complex polysaccharides enhance soil structure, increasing porosity in clay soils while improving water retention in sandy soils. Field trials demonstrate significant increases in soil organic matter content, providing long-term agricultural productivity benefits (Pardilhó et al., 2023). Moreover, Pardilhó et al. (2023) conducted research demonstrating that beach wrack, mainly composed of brown macroalgae, contains significant levels of nitrogen (2.02%) and potassium (2.37%) that make it valuable as organic fertilizer.

Beyond these physical improvements, seaweed components, including flavonoids and polysaccharides, exhibit plant-growth-promoting properties and natural pest suppression capabilities, reducing dependency on synthetic inputs (Silva et al., 2024). These bioactive compounds stimulate plant defense mechanisms and enhance stress tolerance, supporting integrated pest management approaches. This represents the highest-value application but requires more sophisticated processing and quality control. Research has identified specific mechanisms through which seaweed extracts enhance plant growth, including plant growth regulators and compounds inhibiting certain plant pathogens (Miranda et. al., 2021).

4.1.1. Market Positioning

These products address a specific agricultural challenge, soil degradation, that is increasingly recognized as a critical issue. Unlike generic fertilizers competing primarily on nutrient content and price, soil enhancement products can command premium pricing based on long-term soil health benefits and their bioactive properties that provide natural pest suppression and stress tolerance enhancement.

Many coastal municipalities serve agricultural regions where soil degradation is a pressing concern. This creates natural market opportunities within municipal boundaries, reducing transportation costs and strengthening local economic relationships. The bioactive applications represent the highest-value segment but require more sophisticated processing and quality control systems to maintain the integrity of beneficial compounds.

4.2 Growing Media Substitutes

Processed seaweed compost can partially replace peat in horticultural applications, addressing sustainability concerns while providing slow-release nutrition. These substrates demonstrate efficacy in container-grown ornamental plants and vegetable seedlings. Although composting has been widely applied for the stabilization of waste materials and crop residues, composting algae to produce ornamental substrates is a new approach (Han et al., 2014).

Growing media markets offer consistent demand and higher profit margins than basic fertilizers. As concerns about peat extraction increase, alternative growing media are gaining attention in the horticultural industry, creating a market pull for sustainable alternatives. This application aligns with municipal sustainability goals while addressing a specific market need. It is also less sensitive to seasonal agricultural cycles, providing more stable yearly demand.

4.2.1 Geographic Context and Success Stories

European coastal nations have led implementation efforts, with Portugal, Spain, and Ireland demonstrating mature projects moving beyond laboratory scale (Tedesco & Stokes, 2017; Torres et al., 2019). The Solrød Municipality in Denmark provides a particularly relevant example, successfully integrating 90% of cast seaweed from 3.7 km coastline into renewable energy and fertilizer production while addressing contamination concerns through advanced preprocessing (Lybæk & Kjær, 2023).

Several commercial operations now produce seaweed-based agricultural products, though often using cultivated rather than waste seaweed. The geographic distribution suggests that seaweed composting approaches are adaptable to different seaweed species and coastal contexts. However, specific processing methods and product formulations must be tailored to local biomass characteristics and agricultural requirements. This is not a one-size-fits-all solution; it is a framework that municipalities can adapt to their specific circumstances.

5. Barriers and Enablers

Understanding what prevents or enables successful implementation is crucial for developing viable business models. Our analysis reveals that while significant barriers exist, they are increasingly outweighed by enabling factors, creating a favorable window for municipal implementation.

5.1 The Challenge Side

5.1.1. Supply Management

Irregular seaweed deposition patterns complicate operational planning and capacity sizing (Torres et al., 2019; Miranda et al., 2021). Unlike traditional composting operations that receive relatively consistent organic waste streams, seaweed operations experience unpredictability, including seasonal variations, storm-driven events, and climate-influenced supply patterns; a supply challenge distinct from agricultural residues or food waste streams that follow predictable seasonal cycles. Municipal collection must balance tourism needs with processing quality requirements while managing sand contamination issues (Pardilhó et al., 2023). The Køge Bay study demonstrates that this supply variability requires specialized preprocessing infrastructure, as effective sand separation technology proved crucial for economic viability (Lybæk & Kjær, 2023). Energy-intensive drying processes add complexity not typically encountered in conventional biomass processing, representing significant cost components that municipalities must consider when evaluating modular versus centralized processing approaches (Lybæk & Kjær, 2023).

5.1.2. Capital and Technical Requirements

Technical challenges are significant and multifaceted. For example, sand accumulation in biogas reactor tanks and potential damage to cyclone stirrers and macerators require ongoing technology development for optimal collection efficiency (Lybæk & Kjær, 2023). The Køge Bay study (Solrød Municipality) demonstrates that effective sand separation technology is crucial for economic viability, as cyclone separation can reduce sand content from 60-90% to manageable levels of 10-20% (Lybæk & Kjær, 2023).

Moreover, processing equipment, quality control systems, and facility modifications require upfront investment that municipalities must justify against uncertain returns. The reviewed literature reveals limited standardization in processing workflows and quality assessment methods, hindering consistent product quality (Salvador et al., 2025), and energy-intensive drying processes can represent significant cost components (Lybæk & Kjær, 2023). Heavy metal testing equipment represents additional capital requirements that municipalities must consider in their investment planning.

5.1.3. Regulatory Complexity

Many jurisdictions classify seaweed as waste material requiring specialized disposal, creating administrative barriers to valorization. Additionally, underdeveloped product standards complicate certification and compliance. This regulatory classification creates uncertainty that makes business planning difficult.

5.2. The Opportunity Side

5.2.1. Infrastructure Leverage

Municipal composting facilities, beach cleaning operations, and landscaping departments provide an operational foundation that private enterprises lack. The Solrød Municipality case achieved 32,800 tons of annual CO_2 emission reduction while eliminating disposal costs (Lybæk & Kjær, 2023). This case also demonstrates how a municipality's integrated, or synergistic, approach combines beach cleaning operations with biogas production facilities (Lybæk & Kjær).

5.2.2. Market Trends

Rising conventional fertilizer costs improve alternative competitiveness (Tedesco & Stokes, 2017), while Portuguese studies demonstrate seaweed-derived fertilizers achieving price premiums of 2-3x over conventional compost (Pardilhó et al., 2023). Beach wrack contains significant nitrogen (2.02%) and potassium (2.37%) levels that justify premium positioning as organic fertilizer (Pardilhó et al., 2023). The market potential for seaweed-based compost is supported by studies indicating growing consumer willingness to invest in specialty compost products derived from seaweed, reflecting favorable market trends for organic amendments (Waliczek et al., 2020; Walsh & Waliczek, 2020). However, economic viability requires addressing regional variations in agricultural demand, certification requirements, and integration with existing supply chains; factors that remain underexplored in current municipal implementation literature.

5.2.3. Policy Alignment

Increasing policy support for circular economy initiatives creates favorable regulatory and funding contexts, with the EU Circular Economy Action Plan and Blue Economy development policies specifically supporting seaweed valorization initiatives. Municipal interest in cost-effective waste management solutions that reduce disposal costs creates institutional motivation (Salvador et al., 2021).

The Solrød case demonstrates how municipal-scale operations can benefit from avoiding nitrogen and phosphorus pollution of 60 and 9 tons per year, respectively, while carbon sequestration benefits when seaweed-derived materials are applied to soils, creating climate mitigation co-benefits (Lybæk & Kjær, 2023; Torres et al., 2019). However, the literature reveals limited analysis of inter-municipal cooperation frameworks or cross-border policy coordination that could enhance implementation scalability.

6. Municipal Business Models: Four Pathways Forward

Based on our analysis, we propose four business model archetypes specifically designed for municipal contexts (Table 1). Each addresses different municipal circumstances, capabilities, and risk tolerances while leveraging the opportunities identified in our barrier analysis.

Table 1: Comparative Analysis of Municipal Seaweed Valorization Business Models

Business Model	Municipal Role	Key Requirements	Implementation Approach	Risk Factors	Revenue Sources
Municipal Service Integration	Direct operator	Existing composting facilities, beach cleaning operations	Build on current waste management infrastructure	Low - leverages existing capabilities	Cost avoidance, municipal landscaping savings, local product sales
Public-Private Partnership	Raw material provider & facilitator	Collection capacity, contract management	Municipality collects, private sector processes	Medium - dependency on partner performance	Material sales, processing fees, or revenue sharing
Cooperative Biorefinery	Stakeholder participant	Technical expertise access, shared investment capacity	Multi-stakeholder collaborative management	High - complex coordination requirements	Cascading value extraction from high-value to basic products
Distributed Network	Network coordinator	Coordination mechanisms, quality standards	Multiple small-scale operations with municipal oversight	Medium - network coordination challenges	Variable based on local specialization and market access

The choice among these models depends on several municipal characteristics: Existing infrastructure and capabilities, local political and regulatory environments, available partnerships and market opportunities, risk tolerance and implementation timelines, and the scale of the seaweed management challenge.

6.1 Municipal Service Integration Model (Primary Recommendation)

The core concept of this model is to incorporate seaweed collection and processing into existing municipal waste management and park maintenance operations, creating operational synergies while generating new revenue streams. The idea is to transform waste management costs into revenue-generating operations through integrated beach cleaning, composting, and product sales. This is not about adding new operations but optimizing existing ones while creating new value.

The revenue model includes cost avoidance (reduced waste disposal fees) and municipal landscaping savings through internal use. Furthermore, municipalities could offer bulk sales to regional agricultural entities as well as compost sales to local businesses and residents.

As demonstrated in the Solrød case, municipal collaboration with industry partners successfully transformed seaweed waste into renewable energy and fertilizer while achieving significant environmental benefits (Lybæk & Kjær, 2023). The key success factor is treating this as optimizing existing operations rather than a completely new venture.

6.2 Public-Private Partnership Framework

This model combines municipal collection capabilities with private sector processing and marketing expertise through formal collaboration with clear responsibility delineation. The public sector, i.e. the municipality, can provide efficient waste management, specifically collecting and the primary seaweed processing, while the private sector affords commercial expertise in composting, product formulation and development, quality control, and marketing. This model leverages the strengths of both sectors while minimizing their respective weaknesses.

The advantages include accelerated commercialization through private sector expertise, reduced municipal operational burden, access to established distribution channels and marketing capabilities (Miranda et al., 2021), and shared responsibility for quality control and regulatory compliance.

Depending on the municipality's resources, multiple models are possible. Municipalities can receive payment for raw material, charge processing fees, or share product sales revenue based on contribution and risk allocation. In order to succeed, such partnerships must have clear contract structures, aligned incentives, and long-term commitment from both parties. The partnership must also be structured to be able to survive political changes and economic cycles.

6.3 Cooperative Biorefinery Approach

This collaborative model involves multiple stakeholders forming a cooperative enterprise managing collection, processing, and marketing through cascading use principles that maximize value extraction from seaweed biomass. Maximized value recovery through sequential extraction of different components, from high-value compounds for cosmetics or nutraceuticals down to basic compost from residual biomass.

An advantage of this model is the distributed investment requirements and risk across stakeholder groups while creating diverse revenue opportunities through value-added processing (Salvador et al., 2021; Torres et al., 2019). The cooperative structure allows for the sharing of expertise across different domains, especially for regions with strong cooperative traditions, established networks of potential users, access to technical expertise in biorefining, and relatively predictable seaweed supply to support continuous operations.

6.4 Distributed Micro-Enterprise Network

This model established networks of small-scale processing operations, each adapted to local seaweed characteristics and community needs. Rather than centralized facilities, multiple micro-enterprises focus on specific niche applications or market segments within their immediate geographic area. The distributed approach reduces individual investment barriers while creating opportunities for knowledge sharing and mutual support across the network.

Operations can include direct marketing to local agricultural producers, landscapers, and gardeners, with each enterprise specializing based on their regional seaweed types and customer base. This flexibility makes the model particularly suitable for areas with variable or seasonal seaweed supplies, as individual units can scale operations up or down without affecting the broader network (Miranda et al., 2021).

7. Strategic Implementation Recommendations

Moving from business model selection to implementation requires coordinated strategic action. Our analysis reveals three critical areas where municipalities must focus their efforts to ensure successful seaweed valorization.

7.1 Build on Existing Municipal Infrastructure

Successful implementation builds on existing municipal capabilities rather than replacing them. Integrating seaweed processing into current waste management and composting operations minimizes capital requirements while creating operational synergies.

The Solrød experience demonstrates that technical bottlenecks, particularly sand separation, determine economic viability. Investing in preprocessing solutions enables both contamination control and processing efficiency (Lybæk & Kjær, 2023).

7.2 Supply Chain Resilience

To mitigate the unpredictability of seaweed supply, a municipality can design systems capable of managing variable input volumes through modular processing capacity and flexible storage solutions (Miranda et al., 2021). This could include developing multi-source supply strategies and integrating seaweed from different coastal areas to maintain consistent operations. Also, on a practical note, municipalities could establish information-sharing systems for coordinated collection activities and rapid response to major deposition events.

7.3 Market Development

Starting locally, municipalities can begin with their own internal municipal applications, such as landscaping and park maintenance, to establish operations and assess product quality. When internal applications prove successful, municipalities can pursue regional distribution agreements.

This approach builds market pull through demonstrated value rather than relying solely on environmental benefits as selling points. The business case should quantify environmental benefits, such as carbon sequestration, as well as waste disposal cost avoidance.

8.0 Study Limitations

This study has limitations that influence interpretation and generalizability. Our analysis draws heavily from European coastal experiences, particularly Nordic contexts, which may limit applicability to regions with different seaweed species, deposition patterns, or regulatory frameworks. While European coastal nations including Portugal, Spain, and Ireland demonstrate mature projects moving beyond laboratory scale (Tedesco & Stokes, 2017; Torres et al., 2019), and commercial operations now produce seaweed-based agricultural products, the geographic distribution suggests processing methods and product formulations must be tailored to local biomass characteristics and agricultural requirements rather than following standardized approaches. The Solrød Municipality case, while instructive, represents a specific institutional context that may not translate directly to other coastal environments.

The four proposed business models were synthesized from literature analysis and workshop insights but have not been empirically tested in diverse municipal contexts. The systematic review excluded cultivated seaweed research, which could provide relevant processing insights. Additionally, the PowerBio Gate21 workshop involved limited participants from a specific regional context, potentially limiting the representativeness of stakeholder perspectives.

The study did not conduct a detailed technical-economic analysis of processing equipment options or primary market research. Revenue projections rely on a limited case study data that may not represent broader market conditions. Quality control protocols and certification requirements vary across jurisdictions and continue to evolve, creating implementation uncertainty.

Finally, the business models assume baseline municipal capabilities that may not exist in all coastal communities, and long-term sustainability depends on factors extending beyond this study's scope, including climate change impacts on seaweed deposition patterns and evolving regulatory environments.

9.0 Conclusion: From Waste Problem to Value Opportunity

Circular business models for municipal seaweed composting represent more than an environmental initiative: they offer a practical pathway for coastal municipalities to transform operational challenges into revenue opportunities while advancing broader sustainability objectives.

The Municipal Service Integration model provides the most accessible entry point for most municipalities, leveraging existing infrastructure while creating new revenue streams. This approach addresses a fundamental challenge in circular bioeconomy implementation: making circular principles economically viable within existing institutional frameworks. Unlike other waste-to-resource systems that require entirely new infrastructure, seaweed valorization can build incrementally on municipal composting and waste management capabilities, as demonstrated by Solrød's integration approach, achieving both environmental benefits (32,800 tons CO_2 reduction) and economic viability through existing operational synergies (Lybæk & Kjær, 2023).

Acknowledgment: This research was supported by the Interreg Öresund-Kattegat-Skagerrak (ÖKS) project Power Bio (grant number NYPSID 20358661).

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