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Challenges and facilitators in the collection and treatment of aquatic biomass waste for the production of high-value products

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ABSTRACT:
The objective of this paper is to present challenges and propose solutions for the collection and treatment of aquatic biomass waste, specifically beach wreck, such as seagrass and seaweed, in the promotion of a circular bioeconomy.
This paper explores various methodologies for the collection and treatment of beach wrack to optimize the recovery of valuable compounds contained within these biomass wastes.
In order to do so, we identify and assess the efficacy of different collection techniques, including manual collection and mechanical raking, across diverse coastal environments and subsequently, the requirements of the state of biomass in post-collection treatment processes, such as cleaning, drying and quality tests are mapped to analyze the need to enhance the yield and quality of the recovered materials. Utilizing beach wreck as an alternative to virgin feedstock contributes significantly to advancing a circular bioeconomy, and the effectiveness and efficiency of collection techniques are crucial for making waste biomass suitable for the value recovery of the components contained in it.

Keywords: aquatic biomass waste, beach wreck collection, waste valorization, circular bioeconomy, sustainable waste management.

1. Introduction

The global shift toward sustainable and circular economic models has intensified interest in utilizing organic waste as a resource. Among the many types of organic waste, aquatic biomass, particularly beach wrack including seagrass and seaweed, offers considerable promise due to its abundance and bioactive content, and as a source in bio-based construction. However, technical and logistical challenges have hindered its effective use. The motivation for such scope stems from the project Power Bio supported by Interreg Øresund-Kattegat-Skagerak (ØKS), which explores biomass waste streams within the Capital Region of Denmark and Southern Sweden. Power Bio aims to promote

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knowledge sharing among municipalities and stakeholders to develop methods for prioritizing biomass use. This includes encouraging the use of byproducts improving biomass collection from nature and public areas, and sustainable utilization considering economy and biodiversity. Lastly, the project aims to help prepare the market for biomass solutions and foster local innovation and business development. This paper addresses the barriers and facilitators to efficient collection and treatment of seagrass washed up on beaches. The sustainable management and valorization of aquatic biomass waste is an emerging priority in advancing circular economy goals and promoting sustainable coastal development (Verreth et al., 2023). Large volumes of seaweed biomass accumulate, presenting both a waste management challenge and a valuable resource opportunity (Pardilhó et al., 2023). However, the collection and cleaning of aquatic biomass waste remain critical bottlenecks in the value chain. Seaweed waste often contains sand, debris, and contaminants, requiring careful harvesting and post-harvest handling to ensure quality and safety for downstream applications (Rodine et al., 2024; Borges et al., 2023). In many regions, traditional collection methods are labor-intensive and inefficient (Hashoul & Mohamed, 2022), while mechanized approaches are still under development or poorly adapted to local contexts (Dogeje et al., 2025). Moreover, natural seaweed accumulations such as beach-cast macroalgae are highly heterogeneous and variable in composition, further complicating cleaning and processing (Pardilhó et al., 2023; Mora-Soto et al., 2020). Advances in remote sensing and drone-based monitoring are helping optimize collection efforts by providing better data on biomass availability and distribution (Borges et al., 2023; Wilson et al., 2022), yet operational frameworks for large-scale, sustainable biomass recovery are still evolving. Once cleaned, aquatic biomass waste offers wide-ranging opportunities for valorization across pharmaceuticals, food and feed, chemicals, performance materials, and energy sectors (Hadjkacem et al., 2023; Amir et al., 2024; Castro et al., 2022). However, supply chain fragmentation, inconsistent biomass quality, and limited local technology readiness remain significant barriers (Zhang et al., 2024; Hashoul & Mohamed, 2022). At the same time, key enablers such as increasing demand for sustainable materials (Arantzamendi et al., 2023), favorable policy trends (Verreth et al., 2023), and the low or negative cost of waste biomass feedstocks are driving interest in improved collection and valorization strategies (Pardilhó et al., 2023). Importantly, the value of seaweed biomass waste must be understood in a holistic manner, incorporating not only economic but also ecological and social benefits (Rodine et al., 2024; Hall-Spencer & Rasmusson, 2024; Dogeje et al., 2025). To better understand the practical challenges and opportunities in the collection and cleaning of aquatic biomass waste, this study systematically analyzes current practices, technologies, and value chain dynamics.

2. Methods

A mixed-methods approach was used in this study, integrating literature review, field observations and workshops to analyze current approaches to the collection and cleaning of aquatic biomass waste for high-value applications.

2.1 Emperical and practical method

During this study visits to Bogø and Køge bugt has been made to observe collection, testing, drying and packaging of eelgrass.

Eelgrass on beach Eelgrass drying Eelgrass testing Eelgrass packaging

Photos taken by corresponding author.

Furthermore 4 workshops have been conducted, where researchers, municipality officials, private companies (Søuld, Bogø Eelgrass harvester, BrainBotics) shared experiences in collection and treatment of seaweed.

2.2 Literature method

To support the findings presented in this paper, a systematic literature review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. This methodology was selected to ensure transparency and reproducibility in identifying, screening, and synthesizing relevant academic studies on beach wrack management and biomass valorization. A comprehensive search was conducted via DTU Findit and keywords used in combination with Boolean operators included: "beach wrack", "seagrass biomass", "coastal biomass valorization", "circular bioeconomy", "mechanical beach cleaning"," collection equipment" and "aquatic biomass treatment". Searches were restricted to peer-reviewed articles in English. A total of 368 records were initially identified. After removing 102 duplicates, 266 records remained for title and abstract screening and based on relevance, 39 met all eligibility criteria.
Although the method enhances rigor, this review may be limited by language restriction and due to regional differences in beach wrack policies and ecosystem types, some findings may not be universally generalizable. However, the synthesis provides a robust base to inform the practical and policy oriented recommendations discussed throughout this paper.

3. Results
3.1 Manual collection

Manual collection involves the hand removal of biomass and is most appropriate for small-scale operations or ecologically sensitive areas. It allows for selective harvesting, reducing the risk of disturbing habitats or non-target species (Zieliński et al., 2019). This method also minimizes sand displacement and the potential loss of invertebrate fauna associated with beach wrack. However, it is labor-intensive and may not be viable for large-scale accumulations. Manual collection is commonly practiced by municipal workers or local volunteers in protected or natural heritage areas.Additional benefits of manual collection include the ability to maintain community stewardship over coastal

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environments and engage local populations in conservation-based employment. Nonetheless, the cost of manual labor and seasonal variability in wrack deposition can limit the scalability of this method. Furthermore, safety concerns such as handling decaying biomass and embedded litter (e.g., plastics or sharp debris) necessitate proper training and protective gear for workers.

3.2 Mechanical raking

Mechanical raking provides a scalable approach to beach wrack collection, particularly in urban or high-volume coastal zones. This technique typically employs beach grooming machinery to collect and remove accumulated organic material. Nevertheless, its application must be carefully managed to prevent negative ecological impacts such as sand displacement, habitat disruption, and biodiversity loss (Griffin et al., 2018; Morton et al., 2015). Beach topography, tidal influence, and the type and moisture content of biomass all influence the effectiveness of mechanical raking. Recent technological innovations aim to address these limitations by developing lighter, more agile equipment capable of differentiating between biomass and sand layers. The timing of mechanical operations in relation to tidal cycles is another key factor, as machines operating on saturated sand can exacerbate erosion and compact the beach substrate, impacting fauna such as crabs and beetles. Integrating environmental sensors and GPS tracking can enhance precision and reduce over collection.

3.3 Hybrid strategies

Hybrid strategies combining manual and mechanical methods have shown significant promise for sustainable biomass recovery. Manual collection is particularly suited for ecologically sensitive areas or during initial stages of wrack accumulation, where precision and minimal disturbance are critical. Conversely, mechanical ranking is more appropriate for biomass-dense or high traffic zones, where rapid large scale removal is needed (Zieliński et al., 2019). Field studies have demonstrated that integrated collection methods lead to higher biomass recovery while maintaining minimal ecological disturbance. Beyond environmental advantages, hybrid systems offer notable benefits in terms of cost-efficiency and operational flexibility. By enabling targeted deployment of human labor and mechanized equipment, municipalities can optimize resource use depending on local terrain, wrack density, and seasonal variation. For example, tourism-heavy beaches with predictable wrack buildup may justify investment in mechanized systems, while more pristine or protected areas may rely on low-impact manual methods. Real-time data collection tools - such as drone surveillance and satellite imagery - allow municipalities to dynamically map wrack accumulation and allocate resources accordingly. This adaptability enhances the scalability of hybrid systems, making them viable for both small municipalities and large scale costal operations. Moreover, their ability to balance ecological concerns with economic constraints supports long term sustainability, particularly in regions with fluctuating tourist pressures or seasonal storms.

3.4 Collection in the water

Findings in field observations and workshops in the PowerBio project shows that drone recognition of floating eelgrass waste, can be a future way of collecting the eelgrass waste before it reaches the coastline, without being contaminated with sand and other unwanted materials, which could reduce the costs relating to later cleaning of the material. Experiments are currently being made in the eastern and southern part of Sealand by private companies (Søuld and BrainBotics). The experiments are followed by DTU researchers as part of the newly formed network group "The Coastal Network - Beach Washout and Coastal Resources in Denmark and Sweden", which was established in June 2025 as part of the PowerBio project, with members from municipal operators, researchers, authorities, contractors, farmers, and companies from Denmark and southern Sweden (KIMO International, n.d.)

3.5 Post-collection treatment

Effective cleaning is necessary to remove sand, salt, and other debris from the biomass. High-pressure washing and flotation techniques have proven effective for enhancing biomass purity, which is crucial for downstream applications such as bioplastics, compost, and biogas production (Montesano et al., 2013). Separation processes may also include the removal of foreign objects (e.g., plastics, litter) that frequently co-accumulate with wrack, especially in polluted or urban beaches.

Drying is essential to prevent microbial degradation and facilitate transport, storage, and processing. Solar drying, although eco-friendly, is climate-dependent and may be ineffective in humid coastal regions. In such cases, industrial drying systems provide a controlled environment for consistent moisture reduction and preservation of biochemical integrity. Experimental research on similar biomass types, such as olive pomace, demonstrates the feasibility and scalability of such systems for beach wrack.

Batch and continuous dryers, including belt and rotary dryers, are increasingly applied to marine biomass streams. These systems allow for precise control over temperature and airflow, reducing the loss of volatile compounds. Integration with waste heat recovery systems such as those from nearby industrial operations can improve energy efficiency. Storage conditions post-drying, including packaging in oxygen-barrier bags or temperature-controlled environments, are also crucial to preserve material quality for several months prior to processing. Further research is needed and should test solar and industrial drying efficiency in different environmental settings, in order to guide technology adaption across regions, and reduce post-collection losses which is essential for scaling bio-based value chains.

3.6 Quality testing

Quality testing includes laboratory analysis for moisture, organic compounds, and potential contaminants. Specific tests target the composition of carbohydrates, proteins, and lipids, which influence the biomass's suitability for use in bio-based industries. In addition, heavy metal screening is critical in ensuring safety standards, especially for products entering agricultural or food-related markets (Dugan et al., 2017).

More advanced techniques such as Fourier-transform infrared spectroscopy (FTIR), gas chromatography–mass spectrometry (GC-MS), and inductively coupled plasma mass spectrometry (ICP-MS) are employed to identify and quantify high-value compounds and contaminants. Regular testing protocols aligned with ISO standards help ensure batch-to-batch consistency. The development of portable field-testing kits is also being explored to

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provide rapid assessments in remote coastal settings, reducing the delay between collection and processing. However, the feasibility of such integration depends on regulatory acceptance, consistent quality, and technological capacity for biomass transformation (Zieliński et al., 2019).

4. Discussion

Field observations, workshops and literature review show barriers to effective use of beach biomass including unclear legal frameworks regarding ownership and collection rights, insufficient infrastructure for beach wrack processing, and low public awareness of its value. Often, beach wreck is removed and landfilled due to aesthetic concerns rather than environmental reasoning. Policymakers must improve public awareness and initiate targeted campaigns to help shift perceptions from waste to resource, encouraging participation from citizens and local authorities in the circular bioeconomy vision. clarify regulations to support sustainable collection and develop public-private partnerships to build necessary infrastructure, and launch awareness campaigns to shift perception from waste to resource. Coordinated efforts involving municipalities, environmental agencies, researchers, and private sector actors are vital to ensure success (Dugan et al., 2017). This study demonstrates that collection of beach wrack still needs research and development, if the full potential of upcycling the material to higher value products should be reached. The improvement areas include pre-collection strategies and setting standardized cleaning protocols and clear legal frameworks, which might increase the reliability and market acceptance of beach wrack-based products, supply chain instability such as seasonal supply, dependability of local weather conditions, varying quality and high operational costs. A consistent inbound flow of raw materials are essential in commercial use, and therefore the area still needs to receive subsidies for a longer period of time, if using beach wrack as raw material for higher value products should be profitable on an industrialized basis.

5. Conclusion

This study highlights the untapped potential of aquatic biomass waste, particularly beach wrack, as a resource within the circular bioeconomy. Through a combination of field observations, workshops, and a systematic literature review, several key barriers and enablers to the valorization of seagrass were identified. While manual, mechanical, and hybrid collection methods each offer specific advantages, scaling these approaches requires technological refinement, legal clarity, and infrastructure investment. Post-collection treatment and quality testing are essential but limited by inconsistent supply chains and high processing costs. Encouragingly, advances in drone monitoring and pre-coastline collection methods offer promising pathways to reduce contamination and increase efficiency and will be a step away from earlier models of organic waste management like landfilling, composting and agricultural reuse. For these innovations to succeed, coordinated actions across municipalities, researchers, and private actors are essential. A shift in public and institutional perception from "waste" to "resource" will be a decisive factor in realizing the full ecological and economic value of beach wrack.

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