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Case studies for innovative solutions of beach wrack use

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Introduction

This report No 5.1 is one of the main outputs of the Project CONTRA (2019–2021), which was fulfilled within the Program Interreg Baltic Sea Region. The report was prepared within the Work Package 5 "Innovative technologies for beach wrack handling and toolkit" by experts from CONTRA Project Partners. It represents the results obtained in the six case studies in the countries with different management systems: Germany (Islands of Rügen and Poel), Denmark (Køge Municipality), Russia (Curonian and Vistula spits) Sweden (Kalmar municipality and Öland) and Poland (Gulf of Gdansk).
Each case study is presented in separate chapters, which focuses are indicated in the chapter titles (see Table of contents). Technological aspects of different stages of the beach wrack collection, processing and usage (see Figure below), as well as the management and legislative issues are presented. The last chapter is devoted to Estonian experience.
The structure of chapters is generally similar. The chapters focus on different options of utilising of the beach wrack considering it as management object. The opportunities, obstacles and recommendations are highlighted based on existing practices from the case studies. As the aim of this report is to present the details and findings of the individual case studies (plus Estonian experience) a general summary was not formulated. The conclusions and recommendations were prepared as a separate document and presented by Project CONTRA partners in the Policy brief "Towards sustainable solutions for beach wrack treatment" (see www.beachwrack-contra.eu).

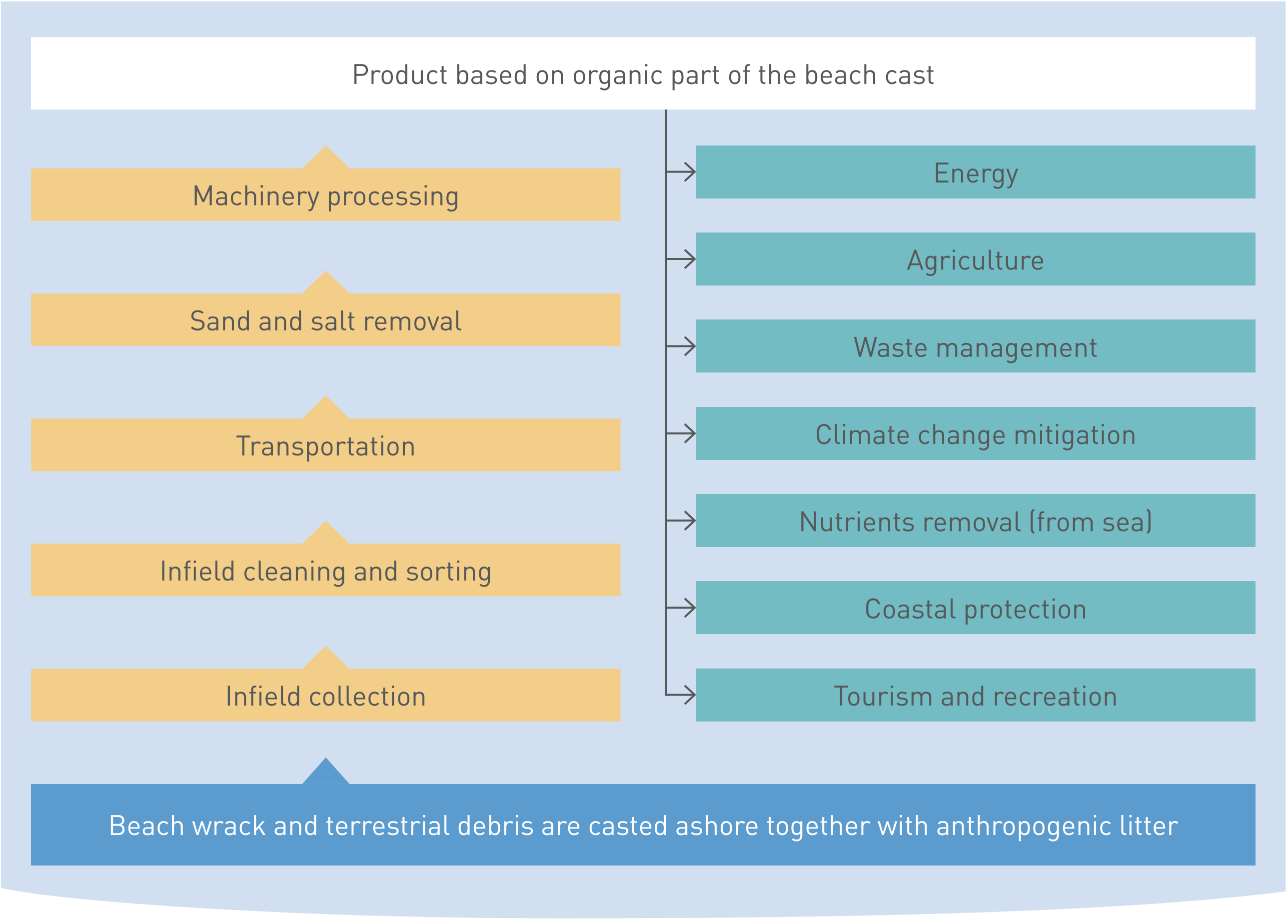
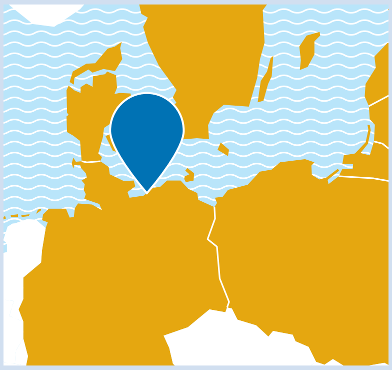


Figure. Phases of the treatment of beach wrack (organic part of a beach cast), which need management, legal and technical solutions (left. yellow), and possible uses of beach wrack born products in different sectors and applications (right, green) [Chubarenko et al., 2021].
Legend: Natural effect | Actions that need better solutions | Products | Usage/Benefit

Case study 1: Beach wrack-based soil production (Wrack4Soil)



Authors: Aldag S., Staemmler M.

Case study partner: Hanseatische Umwelt CAM GmbH

Location of the case study: Bad Doberan/Poel, Germany

Aim of the case study: to improve the process chain of beach wrack for soil production from the technical & management perspective. Development and implementation of new business concepts for beach wrack-based soil products.

Test/research done: Knowledge in co-composting of beach wrack was gained, and new beach wrack-based soil mixtures have been developed. Process technology and methods have been tested, and collaboration with municipalities has been deepened.

Staff involved: Martin Staemmler, Steffen Aldag, Sebastian Staemmler, André Buchwald

1.1 Location and geographical description

The case study region covers the coastline from Travemünde to the Peninsula Darß/Zingst in the federal state of Mecklenburg Western Pomeranian (→ Fig. 1.1). This coastal section is part of the Mecklenburg Bay in the Western Baltic Sea. The composting plant is located in Sandhagen, between the two Hansa Cities Rostock and Wismar. The distance to the coastline is about 15 km.

The Hanseatische Umwelt processes up to 10,000 m³ of compost and various soils per year. In addition to the production of marine biomass compost/soil, the company advises farmers and local authorities, offers services in horticultural landscaping, and is involved in research and innovation projects about marine biomass recycling.

1.2 The effect of beach wrack in the case study area

The Hanseatische Umwelt is processing beach wrack from four beach spots (in four municipalities) within a radius of approx. 50 km to the composting plant Sandhagen (→ Fig. 1.1). The qualitative composition of beach wrack from one beach section varies depending on the season, the collection technique, the duration and type of storage in respective facilities. Every beach spot has its own "typical" dominating plant species in the organic beach wrack composition. In the "catchment" area of 50 km around the composting plant, the common sea grass (eelgrass) *Zostera marina* dominates the beach wrack mixtures. The sand content is an essential parameter for the beach wrack material's machinability and is highly impacted by the beach cleaning procedure and material loading with heavy machinery. The sand content of freshly installed beach wrack piles varies between 50–95 %. The long-term storage of beach wrack in interim storage facilities leads to degradation processes of the organic fraction. It thus hinders further processing, especially the separation of the organic fraction from mineral components.

Figure 1.1 Beach wrack raw material supply of Hanseatische Umwelt (PP14) in the region of Bad Doberan, Germany

Figure 1.2 Temporary beach wrack pile on tourist beach (Island of Rügen, Binz, Germany, July 2014)

One of the four municipalities, the Island of Poel, is cleaning the beaches by itself. Other three municipalities have contracted a service supplier cleaning their beaches, e.g. Rerik, Kühlungsborn and Warnemünde (Rostock).

One of the main suppliers of beach wrack in the case study was the municipality of the Island of Poel. During one season beach wrack material from the Island of Poel needed to be sieved one or two times, and the organic parts were transported to the Sandhagen composting plant. The Island of Poel has a coastline of about 11 km with sandy beaches, while 3 km of them are managed and cleaned regularly in the high season (7 months; from April to October). The overall quantity of beach wrack collected in the managed area varies between 3,500 and 4,500 ton/year, resulting in 166–214 tons per month per km.

1.3 Why is the beach wrack a nuisance in the case study area?

The managed beaches in the region of the case study "Wrack4Soil" are regularly cleaned for touristic purposes. Often, significant amounts of collected beach wrack are stored in temporary piles on or near the beach (→ Fig.1.2). If the temporarily stored material is not processed quickly or stored correctly, leaking leachates and climate-relevant gases (methane, nitrous oxide) can harm the environment. Also, intensive biological decomposition means that organic and mineral components are more difficult to separate by machines.

Looking into an economically valuable processing chain of beach wrack, it has to be considered that the resource beach wrack is only available from managed beach areas. However, the major part of the beaches in the region of "Mecklenburg Bay" between Travemünde in the west and the Darß peninsula in

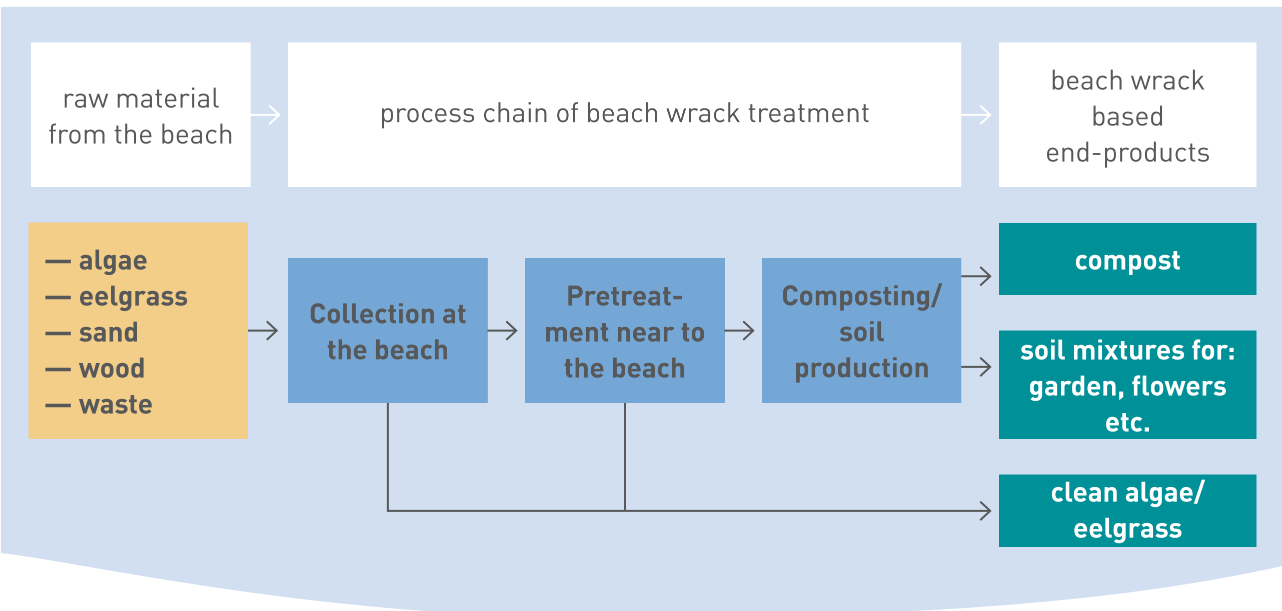


Figure 1.3 Exemplary recycling chain of beach wrack for the production of beach wrack-based soil products and higher-value recycling pathways

Figure 1.4 Collection with a tractor and a beach cleaning vehicle "Beach Tech STR 2000" (Island of Poel, Germany, July 2020)

Figure 1.5 Beach wrack collection in the splash zone using a tractor with a pitchfork and a rake (Island of Poel, Germany, July 2020)

the east are not managed (natural beaches). These beaches are never cleaned from beach wrack material and are partly protected by environmental law.

1.4 Technology and methods of collection and composting

To improve the recycling and supply chain of beach wrack, different recycling pathways in the field of soil improvement products were tested and further developed. The knowledge of co-composting of beach wrack as one of the most promising recycling solutions for the treatment of large quantities of beach wrack was investigated in more detail. Additionally, higher-value recycling pathways for using separated raw materials of beach wrack, such as eelgrass or macroalgae, were part of the case study. For example, washed pure eelgrass can be used as filling material for pillows and mattresses, and clean macroalgae can be used in pharmaceuticals. The main recycling routes of beach wrack considered in this study are shown in → Fig. 1.3.

1.4.1 Raw material supply from the beach site

Beach wrack has to be collected from the beach or the drift line when it is available. Environmental conditions strongly influence the availability, quality and quantity of beach wrack. Thus, the collection method needs to be adapted to the planned recycling options, like composting or processing a single raw material. On the other hand, the beach operator's requirements (e.g. the municipality) must also be taken into account, when recycling the material collected on the beach.

1.4.2 Example of beach cleaning methodology (Municipality of Poel, Germany)

The municipality of Poel is cleaning the beaches with a combination of two different collection methodologies. These methods were studied focusing on the recycling chain's optimisation: how does the collection/cleaning method impact the chosen recycling pathway?

Beach wrack and waste collection in sandy beach areas

To regularly clean the sandy areas above the drift line, a beach cleaning vehicle "Beach Tech STR 2000" is used. This technology is preferably applied to clean the beaches by sieving the fine sand and separation of waste, like crown corks and cigarette buds, rather than collecting fresh beach wrack (→ Fig. 1.4). However, small amounts of dry beach wrack can be collected with this machine.

Beach wrack collection in the drift line

The major part of the beach wrack accumulated in or slightly above the drift line is pushed together by a tractor with a front loader and a pitchfork and a fixed rake in the back of the tractor (→ Fig. 1.5). The tractor's front loader loads the collected material to a truck with a tipping platform or a tractor with a dump trailer for further transportation. The collected material is stored in temporary piles on the beach. Afterwards, the collected beach wrack material is transported to the Poel municipality building yard for storage and further processing (dewatering, screening).

Collection of fresh and clean eelgrass with a stone fork and plastic bags (tested by Hanseatische Umwelt CAM GmbH in June/July 2020)

Experiences with the direct removal of eelgrass with heavy equipment (a tractor with a front loader and a pitchfork) have shown that a lot of dirt, decomposing macroalgae and sand were taken up. Therefore, it is necessary to manually collect the

Figure 1.6 A big-bag trolley for transportation of eelgrass manually collected with a stone fork (Island of Poel, Germany, July 2020)

Figure 1.7 Screening of the beach wrack at the temporary storage facility at Boltenhagen, Germany, July 2020

fresh disposed material in the the shallow waters of the drift line with a stone fork to get clean and sand-free eelgrass. Although this collection method cannot be considered an effective beach cleaning activity, the manually collected material still reduces the total amount of beach wrack that the municipality has to remove from the beach. The collection of eelgrass should be performed as soon as the material is washed up (e.g. after storm events) early in the morning or late at night before the municipality starts the regular cleaning. The eelgrass is collected and transported in 1 m^3 plastic "big bags" for further storage and processing. The big bags can be moved by tractor with a front loader or a small excavator. In case when the heavy machinery is not available or prohibited on the beach, a beach suitable big-bag trolley (up to 300 kg of fresh and wet eelgrass) can be used (→ Fig. 1.6)

As an alternative semi-machinery approach, the eelgrass can be manually pre-collected by a stone fork to get several small piles. The piles are then loaded with an excavator on heavy beach-suitable transport means/vehicles (a truck or a tractor). The manual pre-collection of eelgrass helps to reduce the share of algae, sand and other impurities in the eelgrass. This collection method might also supplement the regular mechanical cleaning by the municipality.

Beach wrack used for composting purposes

Baltic beach wrack collected at the Island of Poel between winter and autumn 2019 and 2020 was used as co-composting material in the case study. Currently, the material is collected by the building yard of the municipality of the Island of Poel. Only managed beach areas are cleaned regularly in the period between April and October. The Hanseatische Umwelt is regularly contracted to screen beach wrack and transport the organic part to the composting plant. In the first treatment phase near the beach, the beach wrack material is usually screened with 20 or 30 mm mesh size in a drum screening plant (→ Fig. 1.7).

1.4.3 Processing and storage of biomass at the composting plant site

The oversize particles (organic) from screening activities near the beach with less sand are transported to be used as, e.g. co-composting material at the plant. The sand fraction with less or only small organic particles is transported back to the beach for coastal protection. Experiences showed that the longer (approx. >2–3 months) the storage time of beach wrack is, the more difficult the separation of sand and organic material becomes afterwards. The continuous decomposition in a pile causes eelgrass to break into smaller pieces and remain in the sand fraction during the screening. This leads to a high organic matter content in the sand, making it more challenging to return the sand to the beach due to its darker colour and regulatory requirements. In conclusion, for the municipality and the beach wrack recycler, quick processing with separation of sand and organic matter would be advantageous.

1.4.4 Washing and drying of undamaged clean and long fibrous eelgrass

The washing procedure of collected pure eelgrass (raw material) is essential to establish a recycling chain for higher value application, like house insulation or filling material for pillows and mattresses. The sand, mud, small algae parts and mussels, other marine debris and the salt stuck to the surface of the eelgrass leaves are washed away using freshwater (rain or tap water). This leads to less

Figure: 1.8 Building of the eelgrass washing unit at the Hanseatische Umwelt CAM GmbH facilities, June 2020)

Figure 1.9 First operation of the washing unit at the Hanseatische Umwelt CAM GmbH facilities, July 2020)

Figure 1.10 Active drying with a fan and an electrical heater in wooden drying boxes at the Hanseatische Umwelt CAM GmbH facilities, July 2020)

Figure 1.11 Passive (pre-) drying on a wooden structure at the Hanseatische Umwelt CAM GmbH facilities, July 2020)

hygroscopic material. After the washing process the intensive smell of the eelgrass transfomes to a slight pleasant smell "of the sea".

It is recommended to use rainwater for making the eelgrass washing environmentally friendly.

Another washing and drying method to clean pure eelgrass is to spread the freshly collected material on green areas to get it washed by rain and dried by the sun and wind. This traditional treatment method was commonly used in the first half of the 20th century in Europe and North America (Wyllie-Echeverria & Alan Cox 1999). Danish farmers still use it.

Installation of a 3-chamber washing system with wastewater treatment

A prototype of a 3-chamber eelgrass and algae washing system was installed at the facilities of the company. The system consists of three open intermediate storage containers (chambers) and a water treatment loop to filter the suspended matter and reduce the nutritional load (→ Fig. 1.8, 1.9). Rainwater is used to wash the mix of beach wrack and sand. Preliminary small-scale washing experiments were conducted. Results showed that fresh eelgrass should be washed at least three times to remove any dirt, algae and sand. Consequently, a 3-chamber system was designed and installed.

After moving the net bag from one chamber to another, the washed eelgrass was pulled out of the chamber to drain the water off. In the prototype, the net bags were moved with an excavator. It seems reasonable to install a kind of beam above the chambers with a sliding pulley system installed on a track, which makes the washing unit more independent from heavy machinery.

Experiences of using the washing unit to wash manually collected eelgrass

Fresh and relatively clean eelgrass was collected using stone forks at the managed beach site "Schwarzer Busch" on the Island of Poel on the 7th of July 2020. Two big plastic bags with totally 293 kg of fresh and wet eelgrass (FW) were collected, resulting in 27 kg of dry weight (DW) of clean material plus 2.5 kg DW of mussels, algae, sand and stones (FW/DW ratio of about 1:10). After the eelgrass was

Figure 1.12 (a) raw eelgrass, (b) shredded eelgrass, (c) eelgrass pellets, (d) eelgrass pellets with added water

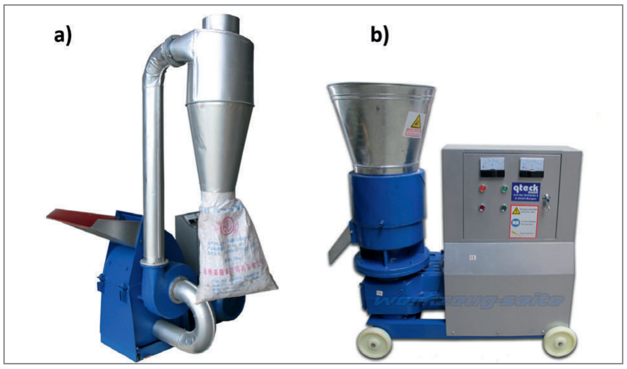


Figure 1.13 (a) Hammer Mill HM 426, (b) pelleting machine PP295UG-S (picture source: https://www.qteck.de/)

washed in the three washing chambers, the drying process, with passive pre-drying on a wooden structure (→ Fig. 1.11) and active drying at the facilities of Hanseatische Umwelt started (→ Fig. 1.10). After seven days, the eelgrass was dry and ready to sell. Before loading the dried material into plastic bags, we had to separate some sand from the eelgrass's roots.

Use of the existing algae and eelgrass drying facilities of Hanseatische Umwelt

The freshly washed eelgrass needs to be dried quickly. The Hanseatische Umwelt has an algae/eelgrass drying room with electrical pre-heated circulating air. The drying facilities are designed for small to medium quantities. Experiences with the drying of fresh washed wet eelgrass have shown, that only a small layer of approx. 5–10 cm of washed material can be placed in the drying boxes (→ Fig. 1.10), and the material needed to be turned up to 2 times a day. The experience with the applied drying method has also shown that it makes sense to pre-dry the eelgrass in the air. For this purpose, we have built a wooden structure, on which the eelgrass can be placed for pre-drying (→ Fig. 1.11).

Figure 1.14 Compost piles with wireless temperature probes at the Hanseatische Umwelt facilities, October 2019

1.4.5 Test of shredding techniques to cut beach wrack components

Dried eelgrass collected with heavy machinery in July 2020 at beaches of the Island of Poel was used to test eelgrass/beach wrack shredding with subsequent pelleting. The eelgrass was not washed but only dried. The material was slightly mixed with sand and algae. A 6-mm screening matrix was used to shred the material before pelleting. Longer fibres of eelgrass were produced by using the 8-mm matrix. The longer eelgrass fibres (15–25 mm fibre length) can be used as a primary material for producing acoustic or insulation boards for building construction. The shredding and pelleting trials were conducted by the manufacturer of the hammer mill and pelleting machine[1]. The machine model No. PP295UG-S with 15 KW electrical power was applied for pelleting (→ Fig. 1.13). These pellets can be used as an organic fertiliser product for regular and balcony gardening (→ Fig. 1.12).

1.4.6 Composting of beach wrack

Preparation of the raw material for composting

The green waste material was shredded with a slow-speed shredding machine (Komptech "CRAMBO 5200 ec direct") with 180-mm mash size before preparing the compost piles. The shredded material was then mixed with 10 % of loamy soil to get a mineral component, needed for the composting process. Clay particles with their large surface improve the biological colonisation of the compost.

1 Manufacturer of hammer mill and pelleting machine: https://www.qteck.de/index.php/maschinen-werkzeuge/energie-und-futtertechnik

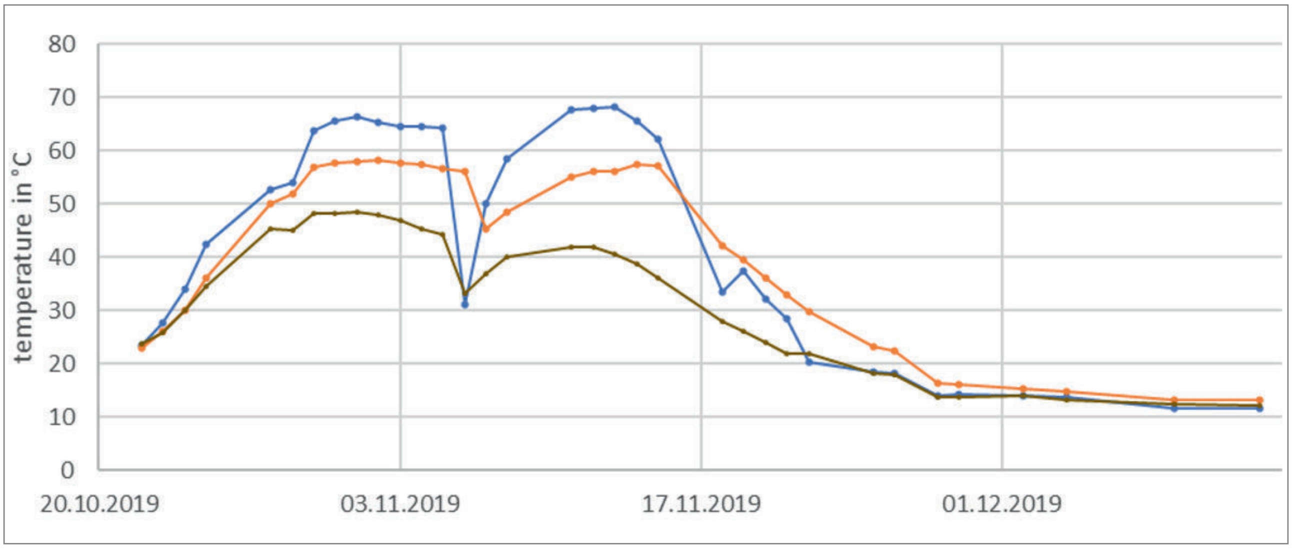


Figure 1.15 Temperature development of decomposition processes in the respective compost piles (100 % green waste (blue line), and the respective beach wrack proportions: 30 % – red line, 50 % – brown line) tested at the Hanseatische Umwelt composting facilities in 2019

Setting up the compost piles

Before the final material mix was put in place, the green waste and the beach wrack were premixed in a cone. A pile with 50 % of beach wrack-share, one with 30 % of beach wrack-share and a pile with 100 % of green waste without added beach wrack have been placed into the compost boxes and covered with a green breathable compost fleece. The material was moved with a small excavator having a 0.5 m³ shovel.

Temperature and CO_2 monitoring

During the composting process, the temperature was monitored continuously using wireless temperature probes (→ Fig. 1.14). The CO_2 content of the compost piles was measured by using a semi-quantitative measurement system. The released CO_2 was pumped through a lance into the measuring cylinder filled with potassium hydroxide solution (KOH). The solution expanded on contact with CO_2 and indicated the volumetric % of CO_2 in the compost gases. Both measurements of temperature and CO_2 (vol. %) indicate the status of the rotting process. The presence of sufficient oxygen and the right ratio of carbon to nitrogen in the biomass of 35/1 leads to an optimal decomposition of organic matter by microorganisms and fungi. Furthermore, the compost should be moist enough for optimal microbial degradation.The decrease of CO_2 and temperature in the core of the compost pile indicates a reduced aerobic microbiological activity of the compost process. In this case, the compost pile is usually turned to bring fresh and nutrient-rich material and oxygen into the core of the compost.

Regular turning of the compost piles

By turning the compost pile, material that has not yet decomposed is re-mixed into the pile from the outside. The rotting process continues, whereby the temperature also rises again. The moving aims to mix the material and supply the compost pile with oxygen.

The sudden minimum in the middle of the diagram shows a turning event of the compost piles (→ Fig. 1.15). After turning the piles, the temperature drops down immediately. However, the temperature rises again rapidly, if the raw material still has enough microbiologically usable energy.

Comparison of temperature development in green waste and beach wrack compost piles

With increasing the share of beach wrack in total biomass (in relation to green waste), the temperature decreased during the decomposition process (→ Fig 1.20). The brown line of 50 % green waste demonstrated this trend, while the temperature didn't exceed the threshold value of 50 °C.

According to the German Regulation on the recycling of biowaste from agriculture, forestry and horticulture (BioWaste Regulation – BioAbfV) the compost material must be disinfected according to the following criteria: "During the aerobic disinfection treatment the temperature of at least 55 °C must be applied continuously to all rotting material for at least two weeks, or 60 °C for six days, or 65 °C for three days. Due to moving the compost pile from time to time, the plotted temperature shows its minimum in the first interval.

Figure: 1.16 Shredding and mixing of green waste and beach wrack

Figure 1.17 Adding additives to the compost

1.4.7 Additional fields of beach wrack application – eelgrass as mulch material

Usually, the strawberry farmers place straw under the adult plants to protect the fruit from humidity and any diseases of fungal infections. Inspired by private gardeners' reporting about several positive effects on fruit development, we tried to use eelgrass for a couple of strawberries plants in the open field on their size and taste. We assume that apart from protecting the fruit from humidity and direct contact to the soil, the eelgrass can positively affect the plant and the fruit growth. The eelgrass covers the soil surface around the plant, keeps the soil warm and reduces the water vaporisation. It is also known that several acids (rosemary and zosteric ones) on the eelgrass leaves' surface protect the eelgrass from biological degradation having an anti-fouling effect [Papazian et al. 2019] that might also protect the plant and the fruit from diseases or fungal infections.

1.4.8 Development of new beach wrack-based soil products at the Hanseatische Umwelt CAM GmbH

In May 2020, a new composting trial with an 18-m³ compost pile was launched. Very fresh green waste was mixed with 8 m³ of fresh beach wrack, that resulted in an approx. share of 30 % beach wrack to 70 % green waste (→ Fig 1.16). Biochar and other mineral additives were added during the composting process (→ Fig. 1.17).

1.5 Management-based obstacles

The Hanseatische Umwelt tried to establish a reliable supply chain with beach wrack material to build up a continuous production of beach wrack products.

One idea was to establish a long-term supply and purchase beach wrack contracts based on an estimated annual average of biomass. A draft contract was presented to the Poel Island Municipality, the associated partner of CONTRA (AP13). Such a long-term contract is difficult to implement for the municipality due to an annually renegotiated budget. On the other hand, other municipalities in the case study area consider a long-term contracting of beach wrack cleaning and recycling services. But the common practice of the municipalities is still to tender for beach cleaning and beach wrack recycling. Due to these uncertainties, the supply of a certain/expected minimum amount of beach wrack biomass cannot be guaranteed over the years. These unsatisfactory conditions make it difficult to develop products, build up processing infrastructure and establish a sustainable, economically viable marketing concept.

1.5.1 Administrative / legal obstacles

The use of compost in agriculture is limited due to the national and EU fertiliser legislation. Knowledge about positive impacts of compost application to agricultural land and its ecosystem services (reducing nutrient leaching, storage of water, long-term carbon storage, etc.) needs to be disseminated to farmers, politicians, and water supply associations.
Besides, the advantages of using beach wrack or beach wrack-based substrates as organic fertiliser and soil conditioner in coastal agricultural zones need to be identified and considered in the fertiliser legislative framework. Using this organic fertiliser could reduce the application of mineral fertiliser in the Baltic coastal region and thus reduce the nutrient input into the Baltic Sea.

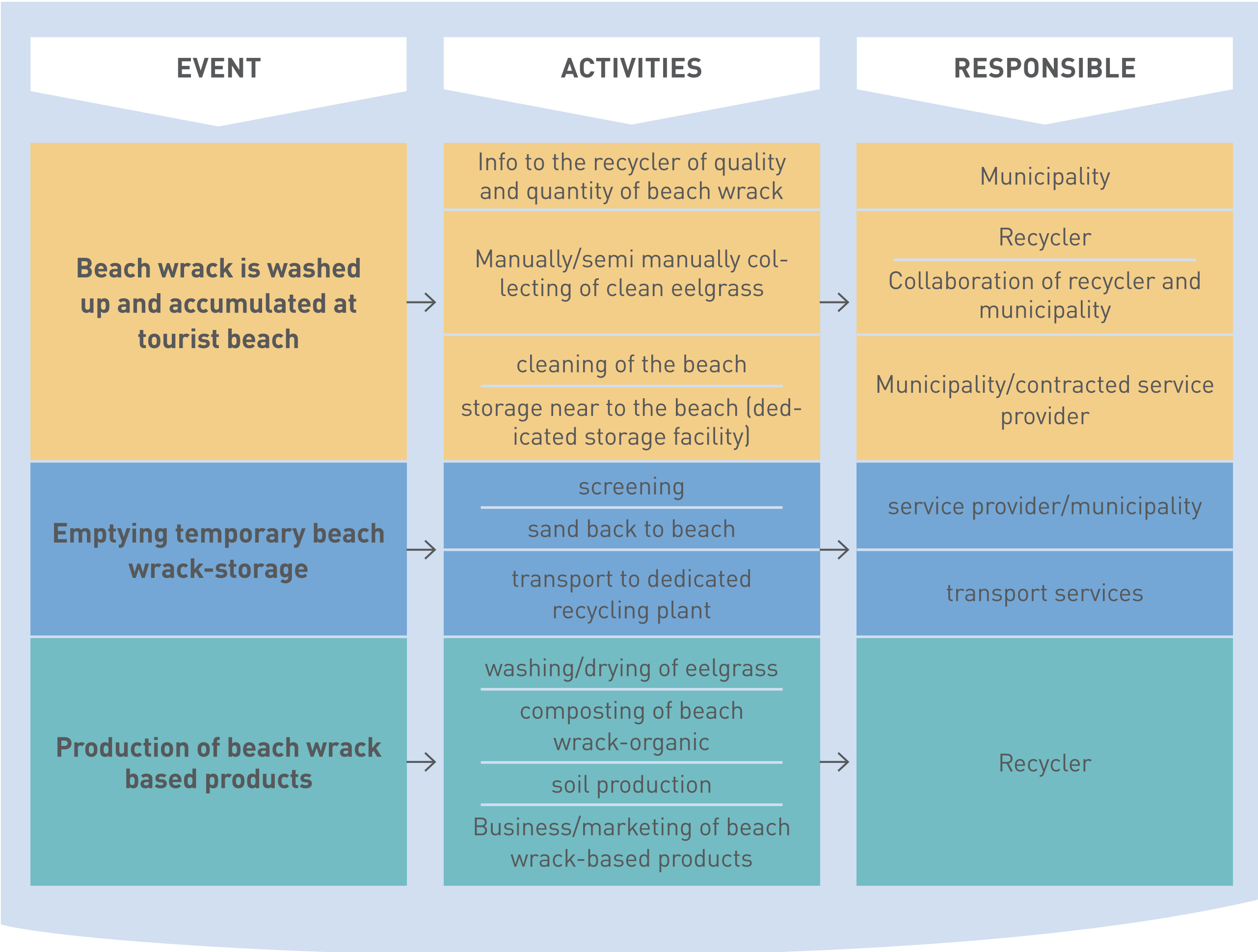


Figure 1.18 Desirable organisation scheme of beach wrack recycling chain in the "Wrack4Soil" case study area

1.5.2 Proposals for potential solutions

One of the significant challenges of building up an economically feasible beach wrack recycling chain is good communication with the municipality, as a raw beach wrack-material supplier. The way of cleaning the beaches (technical method) and the time of response between the appearance of beach wrack and the cleaning activities start significantly influence the quality of beach wrack. Therefore, directly after the occurrence of beach wrack, a process of communication between the municipality and the recycler in charge must be initiated. This is especially important when the recycler aims to get high-quality eelgrass/algae before the municipality starts cleaning activities.

→ Figure 1.18 shows a desirable event-based communication flow chart. The chart is not only showing the event and the necessary activities, but also a responsible party. Regarding the quality of screened material, it would be much appreciated to conduct the screening of the material directly after the beach's collection. This will increase the material quality and reduce the temporary stored material's biological degradation with its negative environmental effect resulting from leachate and methane emissions.

1.6 Conclusions

Different recycling pathways of beach wrack to produce soil products were tested during the case study "Wrack4Soil". One of the significant challenges in practical implementation is establishing recycling processes that are tailored to the availability and quality of the raw material with municipalities playing the role of beach wrack-suppliers. To further develop recycling methods for beach wrack, it should always be considered that material can only be provided from managed beaches. Thus, it is important to know the municipalities' requirements and build up a close partnership with them. Different recycling pathways, as well as processing methods, were tested. The focus was on the co-composting of beach wrack as one of the most promising recycling solutions for significant amounts of mixed beach wrack material. In addition to studying the recycling chain and processing methods, various applications of beach wrack in the processed or raw form were investigated.

1.6.1 Potential solutions

Composting

The recommended recycling method of mixed and dirty material (wood, plastics, plants, sand, etc.) is the co-composting of beach wrack with terrestrial green waste. Therefore, the presented case study had its focus on the co-composting of beach wrack. The industrial thermophile composting method lead to fast remineralisation of a large amount of heterogeneous organic material. During this process, pathogenic bacteria and germinable seeds and several organic pollutants are eliminated by the compost's microbiological colonisation. Researchers recently reported a high degradation rate of microplastics in hyperthermophilic composting [Chen et al., 2019].

The advantages and disadvantages of beach wrack composting are as follows:

Pros:

- large quantities of beach wrack are processed;
- sand content is favourable for soil structure (≤ 30 %) because sand particles aerate the soil and provide mineral content while composting;
- disinfection of biomass by high decomposition temperatures;
- degradation of possibly existing organic pollutants;
- long-term carbon sequestration;
- established and approved process and documentation procedure, especially concerning pollutants and other components.

Cons:

- time-consuming and labour intensive;
- licensed recycling company required;
- mechanical effort (moving, screening, transportation);
- monitoring and documentation obligations.

Processing of raw and separated eelgrass

The case study was also intended to address harvesting and processing the long-leave eelgrass material, which can be used for mattress and pillow fillings. Practical tests on the beach and at the composting plant confirmed that purely mechanical collection as part of regular beach cleaning does not produce high-quality material. Subsequent processing of heavily contaminated material (sieving, washing, etc.) is very labour and energy-intensive. Therefore, if a recycling chain for high quality and high-priced eelgrass needs to be established, it is necessary to harvest the material independently of the regular beach cleaning. Once the material is contaminated with sand, algae and litter by the use of heavy equipment, it can usually no longer be used for higher-value applications. Still, it can be used as mulch material in gardening or directly in composting.

With regard to the economic exploitation of high-quality eelgrass, the greatest challenge is still the fluctuation in quality and quantity. Furthermore, there is a seasonal concentration of eelgrass accumulations in late summer and autumn. This means that personnel and equipment must be ready to work as soon as the eelgrass is washed up. Here it becomes clear that a business model that exclusively focuses on the harvesting of eelgrass cannot work economically. Instead, combining other business areas, such as washing and processing agricultural products (e.g. herbs, salads) should be considered. Investments in professional sorting, washing and drying equipment can only be made if the machines and personnel are fully utilised throughout the year.

The main findings of the collection and processing trials of eelgrass carried out are as follows:

- Collection of eelgrass independent from regular beach cleaning is necessary.
- Eelgrass collected by heavy machinery cannot be used for high-value applications anymore.
- A combination of manual (a stone fork) and mechanical (a tractor, a front loader) work is possible, and synchronisation of "cleaning" and "harvesting" is crucial.
- Eelgrass collection needs to be integrated into the overall beach management of the municipalities.
- Eelgrass processing needs to be combined with other agricultural business sectors (herbs/salads production) for economic success.

Development and production of new soil mixture with beach wrack-based compost

High quality and mature compost is a valuable soil conditioner and organic fertiliser and the basis for the production of commercial cultivation substrates (soil mixtures) for various applications, like lawn areas and private gardening. Many of the soil mixtures produced at the Sandhagen Composting plant already contain beach wrack-based compost. To increase marine biomass recycling's added value, we developed a new beach wrack-based soil mixture for particular use in private regular and balcony gardening.

Selling high-quality soil products, at a higher price per kg, will increase the added value. On the other hand, it will make it possible to reduce the cost burden of the municipalities for beach cleaning and recycling of beach wrack.

The idea of producing new beach wrack-based soil mixtures was to emphasise the unique selling proposition of beach wrack with its known effects on plant growth and health and rediscover the knowledge of traditional use of beach wrack in agriculture.

The other important marketing aspect is the sustainability of the product. It is produced based on local raw materials without the addition of peat. The use of environmentally friendly and plastic-reduced packaging illustrates the claim to produce a sustainable and holistically designed product. The most essential identified product properties are:

- an added value of beach wrack;
- locally and sustainably produced high-quality soil without peat, as a marketing concept;
- rediscovering the knowledge of traditional use of beach wrack in agriculture and gardening.

1.6.2 Findings of the case study

Achieved improvement

- Improvement of the partnership with municipalities;
- The first step to establish the continuous raw material supply of beach wrack;
- Development of marketing concepts/product labels for existing beach wrack-based products of the Hanseatische Umwelt (beach wrack-based compost);
- Development of new soil products with beach wrack as a unique selling proposition;
- Increased added value through product development;
- Increasing awareness about the advantages of compost use.

Technical issues

- Co-composting with 30 % of beach wrack (and 70 % green waste) seems to be optimal.
- Long-term storage reduces beach wrack quality due to nutrient loss and degradation processes (methane, leachate).
- Quick screening of beach wrack after collection could be beneficial for the recycler and municipality.
- Sand share of up to 30 % of the weight is tolerable for composting.
- Collecting raw, clean eelgrass from beaches needs manual work and/or a combination of manual and mechanical work.

Legal issues and identified obstacles

- Establishment of continuous material supply is difficult.
- Close cooperation of the recycling company and the municipality is crucial.
- Tendering for beach wrack recycling services makes it difficult to plan production (a still common practice).
- Long-term contracts with municipalities need to be negotiated.

Case- and site-specific challenges

- Continuous raw material supply is crucial for scaling up the production.
- Risk of being dependent on beach wrack supply for product manufacture is still high.
- Treatment of eelgrass needs to be combined with other agricultural business sectors (herbs/salads production).

Case study 2: Bio-coal from beach wrack (BWC)

Authors: Garrels T.

Case study partner: KS-VTCtech GmbH

Location of the case study: Island of Rügen, Germany

Aim of the case study: to prove the concept of producing biochar from beach wrack, to determine the properties of biochar made from beach wrack, and to assess the economic feasibility of a treatment plant.

Test/research done: Carbonization tests, laboratory analysis of biomass and biochar.

Staff involved: Timo Garrels, Klaus Serfass, Bernd Rogge

2.1 Location description and the tourist situation

The Island of Rügen (→ Fig. 2.1) is the largest and most populated island of Germany. It is located on the northern shoreline of Mecklenburg Western Pomerania, and can be reached by bridge from the city of Stralsund. With 77,000 permanent inhabitants and around 7.2 million overnight guests (2019) [Graefe, 2020], it is the most important touristic location in the German Baltic Sea region.
The main touristic hotspots are located on the eastern shoreline, ranging from Kap Arkona (the northern tip of Rügen) over Breege / Juliusruh with the largest beach on the island, Glowe, Lohme, Sassnitz, Binz, Baabe, Sellin, Göhren to Thießow (the south-eastern tip of the island).
Since the island's eastern shoreline is also the area with the highest emergence of beach wrack (→ Fig. 2.1), which is seen as a nuisance by the majority of tourists, local communities and tourism administrations struggle with beach cleaning and beach wrack disposal during the tourist season, which is mainly from May to September.
The western and southern shoreline of the island does not suffer from large beach wrack quantities. Since the area is not of much touristic importance, there is little demand for collection and disposal of beach wrack in that area.
The actual growth of beach wrack, a mixture of seagrass, seaweed and various algae, along with other debris, mainly happens at higher water temperatures in summer. However, in the context of this study, it's not the growth time that is relevant, but the time of the release of the material on the beach. Depending on the wind direction and weather conditions, this happens more or less throughout the year, but the beaches are only cleared during the tourist season.

2.2 Assessment of the beach wrack yield

Both Associated Partners of case study (CS) 2, the municipality of Sellin (AP14), and the municipality of Breege/Juliusruh (AP15) (→ Fig 2.1) perform beach management activities during the season of May – September, but could not provide reliable data on the exact amount of beach wrack they had collected and disposed of during the term of the project.
On the one hand, they do not weigh beach wrack during collection or transportation from the beach; on the other hand, they usually do not dispose of the material on the per ton cost basis, therefore, they do not need the recording of mass data.

Figure 2.1 Island of Rügen, Germany – the main area of beach wrack emergence

The municipality of Sellin (AP14) has a beach length of roughly 1.6 km and removes the beach wrack daily during the beach management season. Some sand is separated on-site, and then the collected material is transported to a municipal composting facility. The collected beach wrack mass can be estimated at roughly 200 t/a, including an unknown amount of remaining water and sand.

The municipality of Breege/Juliusruh (AP15) has a total beach length of 8.5 km, of which around 1.5 km are being managed during the season. Beach cleaning is done on demand, and the picked-up material is usually stored on an unmanaged part of the beach.

The total beach wrack emergence in the area of Rügen is impossible to quantify since there is no official data available. Our estimations come to roughly 30 thousand m^3 per year, of which less than 50 % is collected and disposed of during the beach cleaning season. Since the picked-up material can contain large weight fractions of water and sand from the beach, beach wrack organic dry matter can only be roughly estimated at around 1–2 thousand t per year.

Beach cleaning options and obstacles

Beach wrack is a collective term for all kinds of marine plants, algae, wood, debris, waste, animal carcasses, etc. Therefore, depending on the regarded area and season, there can be considerable differences in the appearance of beach wrack within the case study area.

On the island of Rügen, beach wrack material varies from coarse and fibrous materials like fresh seagrass to fine algae materials that appear to be almost liquid. During the case study, we could not identify any dependency on a particular season or location.

The beaches on the island of Rügen are only cleaned during the tourist season. The tourists, who visit the island mainly for a beach holiday, expect well-tended beaches from the tourism administrations. Not to hinder tourism, which is the main source of income on the island, beach cleaning usually occurs in the evening and early morning hours.

2.2.1 Common beach cleaning machines

To this day, machines used to clean the beaches are the ones commonly used in construction and agriculture: wheel loaders, excavators, and tractors with trailers for removing the material. These machines are robust and durable, but not specifically designed for the beach cleaning purpose.

As a result, the cleaning performance is very different depending on the material to be removed, and the cleaning quality is limited. A significant amount of beach wrack remains on the ground, or a large amount of sand is removed along with the biomass. To remove beach wrack from large beach sections in a short time, specially designed machines would be required. The already mentioned considerable differences in the appearance and structure of beach wrack in the region further complicate a fast and thorough cleaning of the beaches, because the different machines deliver different cleaning results for the respective material structures.

In general, using agricultural machines for beach cleaning appears to be a good idea, since beach cleaning is only carried out during the summer months. Therefore, the equipment used by the municipalities can also be used for winter services (snow removal, a sprinkling of salt on frozen roads, etc.) and maintenance of public green areas.

In the case study area, some municipalities sometimes commission a waste disposal company to have the beaches cleaned, if necessary. Others do the beach cleaning themselves. Sometimes external waste management companies are called in as support when large amounts of beach wrack have to be dealt with in a short time. In contrast, the "usual daily emergence" is dealt with by the municipality's own workforce and machinery.

Figure 2.2 Beach cleaning with an amphibious vehicle (Sassnitz, Germany, April 2019)

2.2.2 Amphibious vehicles

In April 2019, we did a beach cleaning trial with an amphibious vehicle ("Truxor", → Fig. 2.2).

This flexible vehicle can drive on tracks and swim on the water. It can be equipped with various attachments and tools to carry out the most diverse work on lakes and ponds. The available equipment includes various cutters, pumps, rakes, screens, skimmers, spreaders, diggers, milling equipment, choppers, rams, as well as shovels, grabs and forks. The overall capacity of the system is suitable for its primary purpose, i.e. maintenance of lakes and ponds. Still, for the efficient removal of the beach wrack from tourist beaches, the vehicle does not perform better than a wheel loader regarding the cleaning quality, the cleaned area per hour and the contamination of the beach wrack with sand.

The ability to swim may be an advantage sometimes. Still, since harvesting beach wrack from the shoreline before it reaches the dry ground is not allowed in Mecklenburg-West Pomerania, this technical advantage doesn't differ.

2.2.3 Specialized beach cleaning machinery

Special beach cleaning machines, such as the "Beachtech" series from the Kässbohrer Geländefahrzeuge AG (→ Fig. 2.3), are available on the market. These are primarily designed to remove cigarette butts, bottle caps, etc. from sandy beaches and are not suitable for removing beach wrack in large quantities. A discussion with the company's technical field service in February 2019 showed a possible interest in cooperation in developing such technology, and the absence of available technical solutions nowadays.

2.3 Other available biomasses for co-treatment

The main scope of this case study was the evaluation of biochar production from beach wrack by using the VTC ("vapo-thermal carbonization") treatment system. Before the CONTRA project started, it became clear that a VTC system to be created exclusively for the treatment of beach wrack would be too expensive both to build and operate in an economically feasible way.

Experience has shown that various other biomasses can be co-treated in VTC systems along with the beach wrack without any problems. In general, all biomasses that are usually treated at compost and biogas plants are also suitable for VTC systems. The same can be said for leftovers from composting and fermentation plants, such as the digestate and the coarse fraction from compost

Figure 2.3 Beachtech 2000 [Kässbohrer Geländefahrzeug AG]

screening after the respective treatment.
We have assessed suitable biomasses for co-treatment (like a green-and-garden waste, food residues from hotels and restaurants, roadside green waste, etc.) that could be available in the case study area. We conducted three surveys (January 24th, 2019, July 18th, 2019 and February 27th, 2020) by mail and email involving a total of 59 waste management companies, composting plants and municipalities in Mecklenburg Western Pomerania. However, the responses were relatively sparse, and in no way representative for the size of the region.
As we were unable to obtain meaningful data on the available amount of biomass that could be treated along with beach wrack, we decided to use a different approach for dimensioning the appropriate size of a VTC plant for the economic part of the case study. Therefore, we calculated a comparatively small annual throughput for a showcase plant's design and the associated profitability calculations. Using this approach, we hope to be on the safe side since, if the actual quantities turn out to be larger, this can only improve the plant's economic efficiency.

2.4 Biochar applications and the VTC process

2.4.1 The VTC process
With Vapothermal Carbonization (VTC), KS-VTCtech GmbH has developed a very robust batch process that can convert any biomass into a long-term storable and high-calorific product "biochar" (a more scientific term is "biomass carbonate").
Biochar is a collective term for various types of carbonized biomass that can be produced in different ways. Hydrothermal and Vapothermal Carbonization, torrefaction, and pyrolysis are technically different processes with different reaction conditions and temperatures. Still, they are all essentially aimed at producing higher calorific value materials from more or less fresh biomass.

Figure 2.4 an experimental VTC reactor

The VTC process is a thermo-chemical process, in which the natural formation of coal ("coalification") is reproduced within a few hours by using high pressure and heat. During the process, the relative carbon content of the biomass is increased at 220 °C and 23 bar in a pressure vessel with the reaction time of about 3 hours. VTC is not susceptible sensitive to contaminants, hence the input biomass does not have to be pretreated.

2.4.2 Treatment methodology
The respective sample was filled into the reactor (→ Fig. 2.4) along with an excess amount of water. Then the system was heated up. When the reaction chamber reached the temperature of 220 °C, the timer was set for 3 hours, and after completion, the steam was released from the test reactor. The sample was removed and left to cool. Then it was packed and delivered to the laboratory for analysis.

2.4.3 Biochar and ways of its utilization
The resulting biochar can be used as a replacement for fossil fuels, like lignite and hard coal at thermal power plants, cement plants, and other industrial combustion processes. The quality of biochar (calorific value, carbon content, ash content) can be influenced to a certain extent by the reaction time, but it mainly depends on the input biomass. Usually, the biochar in the range between lignite

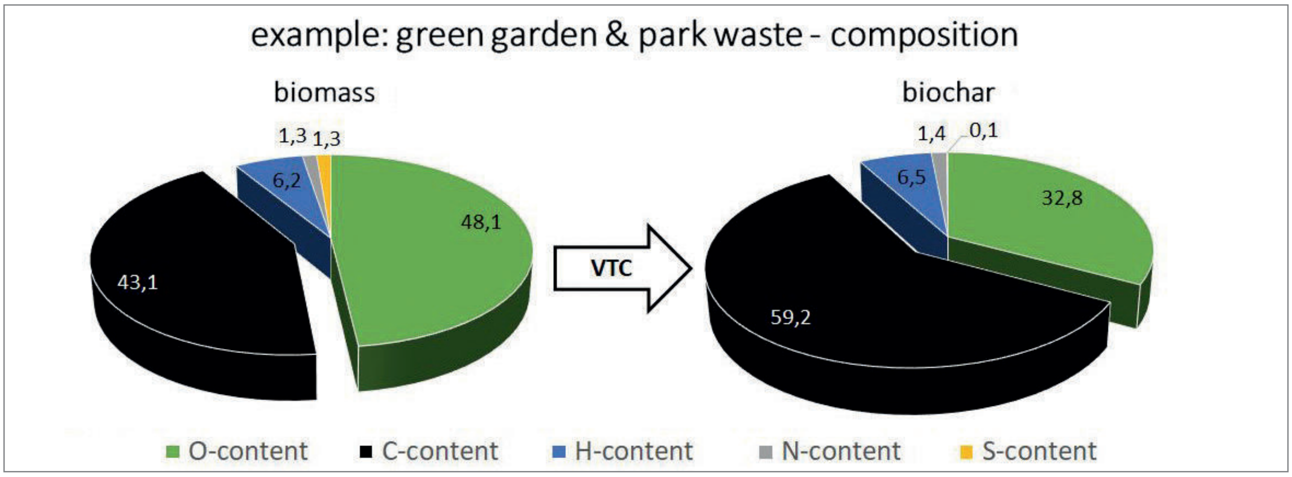


Figure 2.5 carbon proportion change during the Vapothermal Carbonization

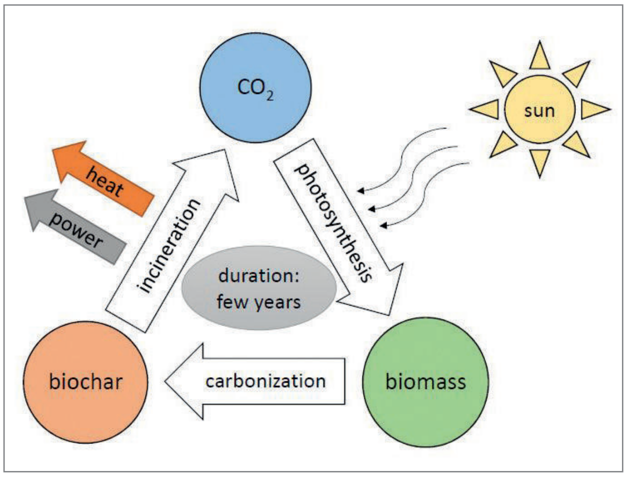


Figure 2.6 short-term carbon cycle

and hard coal can be reached within economically viable reaction parameters.

During the VTC process, the relative proportion of carbon in the biomass increases (→ Fig. 2.5) by thermal splitting off other atoms and molecules from the biomass. Around 700 kg of dry biochar remains from 1 ton of the input organic dry matter.

In addition to hydrogen and oxygen, nitrogen, sulfur and other elements of the biomass are also driven out of the molecules, which means that the process also produces water (steam) and various other secondary compounds in addition to the biochar. Inert components (ash, stones, sand, metal parts, etc.) are not affected by the process, and leave the reactor in the same way as they have entered it with the biomass.

The quality of biochar strongly depends on the composition of the input biomass. Biomass with a high ash content leads to biochar with a correspondingly high ash content, which harms the product's calorific value.

2.4.4. Biochar is carbon neutral

Since the biochar is made from "fresh" biomass, it can be considered a carbon-neutral fuel compared to fossil coal. It doesn't produce any additional CO_2 in short-term scale. The CO_2 released during the combustion of biochar has been removed from the atmosphere in recent years by photosynthesis during the biomass growth used for producing the biochar. In that context, the biochar use is a closed short-term carbon cycle (→ Fig. 2.6).

2.4.5 Marketability

The subject of pricing carbon emissions has become more and more into the focus of economic considerations during the last years. Most recently, a national system for carbon emission pricing was created by the German Government.

In December 2019 Germany's federal and state governments agreed to fix the price for CO_2 emissions at the rate of EUR 25 per ton of CO_2 starting from January 2021. After that, the price will gradually increase each year until it reaches EUR 55 in 2025. A price corridor between EUR 55 and EUR 65 shall then apply for the year 2026.

The details are regulated in the Law on a national certificate trading for fuel emissions – "Gesetz über einen nationalen Zertifikatehandel für Brennstoffemissionen (Brennstoffemissions-handelsgesetz – BEHG)". Solid fuels, such as coal, will be included from 2023 onwards. Therefore, the use of fossil coal will become correspondingly more expensive for consumers.

When lignite is burned, around 2.7 tons of CO_2 are released per ton of lignite, while in hard coal the emission factor is around 2.2 tons of CO_2 per ton of coal. Therefore, the use of fossil coal will become much more expensive, as shown in → Table 2.1.

year	2023	2024	2025	AS OF 2026
CO_2 emission price	35 €	45 €	55 €	55–65 €
Additional price per t: lignite	94.50 €	121.50 €	148.50 €	148.50–175.50 €
Additional price per t: hard coal	77.00 €	99.00 €	121.00 €	121.00–143.00 €

Table 2.1 German emission allowances and coal emission prices for 2023 [§10 BEHG]

Since the emission price will be paid for by the distributor of the coal (coal wholesaler or coal importer) in the first place, it is to be expected that these costs will be added directly to the sales price of the corresponding coal type. Thus, consumers will not have to deal with a complex emissions trading system, but they will feel the rise in solid fuel prices after 2022.
By then at the latest, the demand for alternative solid fuels, such as biochar, should increase significantly, since due to its material properties, carbon-neutral biochar is suitable for substituting fossil coal in co- or mono-combustion systems.

2.5 Properties of biochar from beach wrack

Since KS-VTCtech GmbH deals with the application of VTC, the biomass experimented within this case study (beach wrack and other biomasses suitable for co-treatment) was treated accordingly.

2.5.1 Biomass pretreatment and storage

Most samples were collected in 2019 and were carbonized freshly. Some were dried first, and some had already been collected in 2017 and 2018, then dried and stored. Since no significant systematic differences in the properties of the biochar, depending on previous drying or more extended storage, were observed in the course of the study, an evaluation of different pretreatment or storage methods was not carried out.
However, from experience we know that the carbonization reaction essentially influences the composition of the organic substance in the biomass; the inert components (sand, stones, ash, clamshells) contained there, leave the carbonization reactor unchanged.
Since the carbonization of the biomass is carried out to produce a high quality high calorific value biochar as a substitute fuel for combustion processes, the treated biomass should contain the highest possible proportion of organic dry matter before the carbonization process.
All above leads to the conclusion that biomass should be stored so that no composting or fermentation reactions can occur, since these also consume a proportion of the organic substance and, therefore, lead to a lower calorific value in the biochar.

2.5.2 Relevant parameters

Depending on the technical design of a combustion furnace (lignite/hard coal/biomass heat-and-power plant, cement plant, steel plant, etc.), different fuel parameters can be more or less relevant for the suitability of a particular fuel.
Since there was no focus on specific combustion technology, the suitability of beach wrack for the production of biochar was examined in general. Therefore, we limited ourselves to a few particularly relevant parameters when examining the biochar produced. The main parameters of the biochar are its calorific value and ash content.

Calorific value

Suppose biochar is produced as a substitute fuel. In that case, the product's essential property is undoubtedly its calorific value because it characterizes the specific energy released when a substance is burned. The calorific value depends on the chemical composition of the fuel, and it is also influenced by the material moisture and the mineral content (inert substances, ash content). Since the fuel's moisture content can be directly influenced relatively easily by drying, it will not be further considered here. Further, we put attention to the calorific value based on the dry substance.

Ash content

The ash content of fuel has a considerable influence on the calorific value, since the inert part of the fuel does not contribute to the combustion energy, but comes mixed with the fuel. Accordingly, it reduces the nominal calorific value of a fuel linearly, when considering calorific value per unit weight.
The incineration ash (i.e. the mineralized residue from the chemical conversion of the actual fuel) is the useless residue after the combustion process.

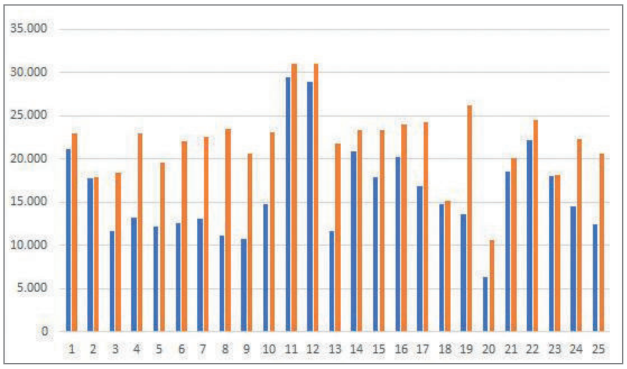


Figure 2.7 Calorific value [KJ/Kg] comparison chart (25 samples), biomass and biochar, blue – the lower calorific value (dry matter), brown – the lower calorific value (dry matter without ash).

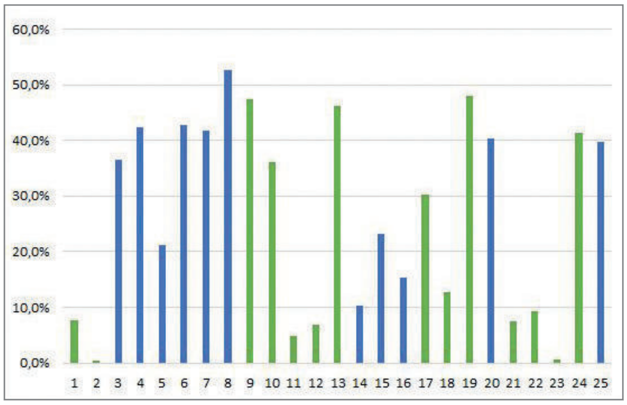


Figure 2.8 Ash content comparison chart (dry matter proportion, 25 samples), green – land-based biomass (wood, bio waste, food waste, green & garden waste, etc.), blue – marine biomass (beach wrack, algae, seaweed and reed).

The expected amount of incineration ash is relevant for the discharge system of an incineration plant.

2.5.3 Main analytic results

Concerning the calorific value and the ash content of the biomass used and the biochar produced, the following data was obtained from the analysis of 25 samples (→ sections 2.6.4, Fig. 2.7 and 2.6.5, Fig. 2.8). The samples 1, 2, 9–12, 17–19, 21-24 (14 samples) present the biochar made from land-based biomass, the samples 3–8, 14–16, 20, 24, 25 (11 samples) present the biochar made from marine biomass.

2.5.4 Calorific value results

All examined samples' calorific value range between about 18 MJ/kg and 26 MJ/kg (→ Fig. 2.7) that is approximately the spectrum between dry wood and hard coal. There is no significant difference between marine biomass (beach wrack, seagrass, algae, etc.) and land-based biomass (garden waste, wood, organic waste, etc.) to be observed.
Exceptions are the significantly higher calorific value of food waste (samples 11 + 12), probably due to the high fat's content, and the lower calorific value of the digestate and the material from torrefaction.
It could be proposed that the result in the case of carbonized digestate (sample 18) was obtained due to the fact that most of the organic matter was already broken down during fermentation. Still, it is questionable, as the fermentation should be recognizable by a comparatively high ash content, which was not the case. However, it may also be due to a measurement error or contamination of the sample.
The low calorific value of the material from torrefaction (sample 20) is probably because the torrefaction is essentially based on a pyrolytic decomposition of the biomass. Therefore, a larger part of the process emerges as a gas with a calorific value higher than during the VTC. However, it is needed to cconsider that here only the solid residue was examined but not the pyrolysis gas.
All the above indicates that marine biomass (and thus also beach wrack) is also suited for the production of biochar using the VTC process, as land-based biomass is.

2.5.5 Ash content results

The results (→ Fig. 2.8) show a comparatively high ash content in the samples of marine origin. Exceptions are the samples made from reeds (14) and the two mixtures of algae and wood (15, 16). This is probably because of the collection technology described in the previous chapters.
In contrast to the marine biomass obtained from beach cleaning, reeds can be harvested very clean, and the algae from samples 15 and 16 were fished from the surface water near the beach before they had direct contact with the beach itself. In addition, these samples were mixed with wood, which already has low ash content and, therefore, also reduces the average ash content in the mixture.
There are also samples of biomass produced on land that typically have a high ash content. This applies in particular to samples from biowaste (9, 10, 13), and digested and liquid manure (17, 19). In the case of biowaste, the cause is probably the lack of selectivity in the collection (soil and sand in the organic waste bin), while in the case of digestate it is mainly due to the fermentation that has already taken place, which also mineralizes biomass.
The sample biochar from mixed wood (24) also shows a very high ash content, but this cannot be explained by an improper collection or a mineralizing

INPUT	amount per year [Mg/a]	dry matter content [%]	bulk density [Mg/m³]	ash content [%]	dry matter [Mg/a]	ash [Mg/a]	organic dry matter [Mg/a]	water [Mg/a]
Green garden waste	15,000	50 %	0.4	6 %	7,500	450	7,050	7,500
Food waste	3,000	25 %	1.0	5 %	750	38	713	2,250
Breach wrack	1,000	20 %	1.0	40 %	200	80	120	800
Total	19,000	44.5 %	0.53	7.6 %	8,450	568	7,883	10,550

Table 2.2 input fractions for VTC treatment plant

pretreatment of the sample. This is more likely to be due to contamination after carbonization.
The carbonization itself also increases the relative ash content of the biochar produced, but not to the extent that would explain a measured value of over 40 %.

2.6 VTC plant technical design and estimated investment costs

2.6.1 VTC plant size

For the calculations presented in the following chapters, we assume an annual treatment volume of 1,000 t of beach wrack, 3,000 t of food waste from restaurants and hotels, and 15,000 t of green garden waste with properties as shown in → Table 2.2.
The amount of material to be carbonized (green waste, food residues, beach wrack) on the Island of Rügen is expected to be at least 19,000 Mg/a. Reliable data regarding the composition of the material to be carbonized is not yet available and therefore the input-material stream is assumed to be consistent over the years of plant operation.
A VTC system with a reactor volume of 48 m³ working in 3 batches per day is required to treat this input mix. Therefore, the plant has to be operated in two daily shifts. For energy efficiency reasons, a VTC treatment plant comprises at least two reactors. To make the given system as simple and therefore inexpensive as possible, a VTC plant consisting of 2 reactors, each 11 m long, is considered in this calculation.
Figure 2.9 shows a possible VTC plant layout corresponding to the case study conditions.

2.6.2 Summary of all analytic results

The table on the following page shows an overview of all results from laboratory analysis:

2.6.3 Estimated investment costs

The estimated investment costs include the required plant technology for the carbonization process, as well as for the drying and screening of the biochar. Mobile devices, such as wheel loaders that are required to operate the system, are taken into account. Concrete and building works are not included either.
A VTC treatment plant, like the one shown above, will add up to approximately EUR 3,350,000.

2.7 Legal framework, plant operation permission and conditions

2.7.1 German Waste Law and the definition of waste

According to the German Waste and Recycling Law (*"Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz – KrWG)"*), waste includes all substances or objects that their owner discards, wants to discard or has to discard. [§3 (1) KrWG].
The producers or owners of waste are obliged to recycle their waste. The recycling of waste has priority over its elimination [§7 (2) KrWG]. The obligation to recycle waste is to be met, insofar as this is technically possible and economically acceptable, particularly for a recovered substance or energy having a market, which already exists or can be created.
Waste recycling is defined as technically possible, even if pretreatment is required. Economic

no.	sample type	remarks / additional information	volatile matter	fixed carbon	ash content	higher calorific value [kJ/kg]		lower calorific value [kJ/kg]	
			% of wet mass	% of wet mass	% of dry mass	dry matter	dry matter w/o ash	dry matter	dry matter w/o ash
1	lignite	from "Lausitzer Revier"	52.7 %	31.7 %	7.7 %	22.191	24.033	21.144	22.898
2	wood	Biomasse Holz HOST	78.7 %	13.7 %	0.5 %	19.383	19.589	17.749	17.838
3	mixed beach wrack	Biomasse Treibsel	50.4 %	11.8 %	36.6 %	12.575	19.839	11.657	18.392
4	biochar from mixed beach wrack	Biokohle Treibsel	40.0 %	11.3 %	42.3 %	13.940	24.187	13.210	22.921
5	seaweed (2017)	biomass	58.6 %	12.5 %	21.2 %	12.871	20.715	12.138	19.565
6	seaweed (2017)	biomass	37.9 %	13.2 %	42.7 %	13.295	23.262	12.589	22.029
7	seaweed (2018)	biochar	42.5 %	13.2 %	41.7 %	13.885	23.831	13.153	22.576
8	seaweed (2019)	biochar	32.9 %	15.3 %	52.6 %	11.827	24.982	11.096	23.439
9	biochar from biowaste	leftovers from composting plant	37.6 %	17.3 %	47.4 %	12.740	24.243	10.798	20.552
10	biochar from biowaste	household biowaste	46.6 %	15.0 %	36.1 %	16.605	25.961	14.741	23.046
11	biochar from food waste	unprocessed food waste	73.7 %	12.4 %	4.9 %	31.299	32.917	29.413	30.933
12	biochar from food waste	processed food waste	74.7 %	28.0 %	6.8 %	30.812	33.060	28.915	31.024
13	biochar mixed biowaste	households & composting plants	39.5 %	32.2 %	46.1 %	13.667	25.484	11.666	21.772
14	biochar from reed		57.9 %	34.1 %	10.4 %	21.662	24.167	20.931	23.351
15	biochar from wood & algae	50 % wood + 50 % mixed algae	39.6 %	22.1 %	23.3 %	18.588	24.231	17.869	23.295
16	biochar from wood & algae	25 % wood + 75 % mixed algae	45.4 %	11.2 %	15.3 %	20.997	24.805	20.260	23.934
17	biochar from digestate	from dry fermentation plant	42.7 %	10.9 %	30.2 %	17.839	25.662	16.897	24.312
18	digestate	from dry fermentation plant	17.4 %	11.8 %	12.8 %	15.701	16.134	14.725	15.131
19	biochar from manure	HTC biochar from manure (kettle)	36.8 %	26.0 %	48.0 %	13.610	26.183	13.610	26.183
20	biochar from beach wrack	from torrefaction	44.1 %	9.6 %	40.4 %	7.029	11.862	6.298	10.635
21	green & garden waste	biomass	70.0 %	10.6 %	7.5 %	19.695	21.311	18.567	20.091
22	biochar from green & garden waste	biochar	59.9 %	0.0 %	9.3 %	23.318	25.722	22.184	24.472
23	mixed wood	biomass	78.7 %	0.0 %	0.5 %	19.483	19.589	18.027	18.124
24	biochar from mixed wood	biochar	44.4 %	0.0 %	41.4 %	15.279	23.494	14.458	22.244
25	bio char from algae	algae from Sellin, April 2019	47.0 %	0.0 %	39.8 %	13.155	21.849	12.424	20.636

Table 2.3 analytic results of biomass and biochar samples (with ash – without (w/o) ash)

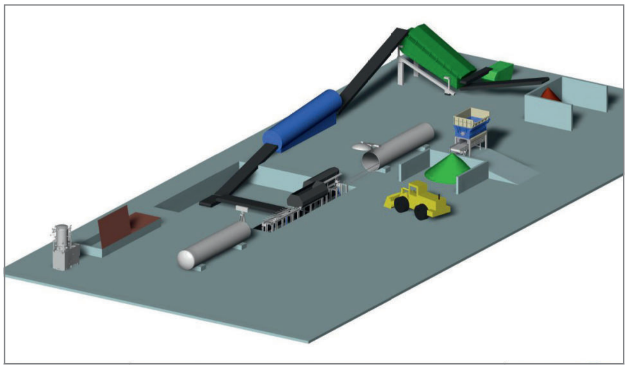


Figure 2.9 Layout example of a VTC treatment plant (VTC 2-11-8) with a capacity of 150 m³/day (reserve 150 m³/day).

acceptability exists, if the costs of recovery are not disproportionate to the costs that would have to be borne by waste disposal [§7 (4) KrWG].
Therefore, when a community or municipality cleans its beaches from beach wrack to keep tourists happy, it legally creates (and takes possession of) a new waste stream that has to be monitored and treated accordingly.
The amount of waste has to be documented. Its transportation and treatment have to be monitored. It can only be carried out by certified waste handling companies or service providers (Entsorgungsfachbetrieb) [§56ff. KrWG], and the final disposal has to be verified. This makes beach wrack collection and disposal complicated and expensive for German municipalities.
Since the dumping of waste in the Baltic Sea is illegal, beach wrack cannot be pushed back into the sea. However, suppose the sea should fetch back the washed-up material on its own, for example, simply due to a wind direction change. In that case, this is a legally unproblematic natural cycle, provided that the material was not touched in the context of beach management.
Many communities take advantage of this fact, at least outside of the tourist season, and hope that the washed-up material will disappear on its own in this way. Of course, this also applies to the many beaches, where there is no beach cleaning done anyway.

2.7.2 Treatment and disposal

Collected beach wrack must be properly disposed of, and depending on the level of pollution (e.g. heavy metals) there are several ways of doing it.
On the Island of Rügen, for example, the beach wrack is sometimes used in agriculture as fertilizer. It has been granted after the special permit if low pollutant content was proven.
If this is not the case, the material must be taken to an appropriately certified disposal facility (composting or fermentation facility, incineration, etc.). Recycling at a carbonation plant is also possible here.
Since all these systems have considerable operating costs and are usually run as private companies, beach cleaning entails the actual costs for collection and transportation and the related disposal costs. Although the problem has been known for many years, there is still no cost-effective, approvable, and scalable disposal method.

2.8 Economic feasibility

This case study aims to develop an example of an economically feasible showcase for the creation and operation of a VTC treatment plant to produce biochar, as a solid fuel from beach wrack mixed with other locally available biomasses.
It was obvious from the start of the project that a treatment plant construction and operation for beach wrack treatment only would not be economically viable, because of the relatively small amount of beach wrack and its unreliable emergence. One possible option was to set up one or more beach wrack storage facilities on the island to optimize the transport routes for the biomass. Due to the island's size and the fact that the vast majority of the beach wrack occurs on the east coast, this interim storage facility will be avoided for economic reasons.
The area around Sassnitz could be a good location for a central treatment facility concerning the logistics of beach wrack. A more central location on the island, e.g. in the area of Bergen, could also be a good choice, considering that the other biomass to be co-treated will probably be delivered from all over the island. Because of its small impact on the overall economic performance, the exact location of the treatment plant will not be considered any further. The same applies to transport costs for the produced biochar since the location of possible biochar customers is yet to be determined.

2.8.1 Plant operation

The delivered biomass is weighed and temporarily stored on the factory premises. It is then visually inspected for coarse contaminants and filled into one of the carbonation reactors using a wheel loader.
During the reaction, the condensate that forms is regularly discharged from the reactor and cooled in a flash tank with a heat exchanger. The cooled condensate is pre-cleaned in a chamber filter

press, as a precoat filter, using flocculants to reduce the amount of dirt. Then it has to be cleaned at a wastewater treatment plant. Since the pressed suspended solids are fine biochar particles, the press cake can be added to the biochar produced and does not have to be disposed of separately.
After the reaction is completed, the reactor is shut down, and the contained steam is used to preheat another freshly filled reactor. After an equilibrium between the reactors is reached, the remaining steam from the first reactor is passed into the flash tank, where it is cooled down to below 100 °C.
As soon as the finished reactor reaches the atmospheric pressure, it can be opened and emptied. It is then refilled with the next batch of biomass and reheated.
The resulting raw biochar is then dried in a continuous dryer, operated with the waste heat from the flash tank. Afterwards, the dried biochar is treated in a 3D-vibrating screen to remove impurities, such as bottle caps, clamshells and stones.
The refined biochar can then be loaded and sold. Further treatment, for example with a pellet or briquette press, is also possible.

2.8.2 Economic assumptions

The following calculations are based on the biomass quantities and its composition (→ Tables 2.1 and 2.2), as well as the estimated investment costs from section 2.6.
The economic assessment was made using the following additional assumptions:

- Acceptance prices for the disposal of biomass ("gate fee"): 40 EUR/t for green-and-garden waste, and 50 EUR/t both for food leftovers ("restaurant waste") and beach wrack.
- The customer's purchase price for lignite is assumed to be 75 EUR/t (as a competitor for pricing our biochar).
- The lignite emission factor is 2.7 t of CO_2 per t of lignite. An annual price increase of 2 % is calculated on all costs and revenues.
- A 30 % discount on the competing lignite price is granted (biochar is sold 30 % cheaper than competing lignite) to achieve a cost advantage.
- The funding for plant construction and operation is calculated in the form of an annuity loan with 25 % equity, 3 % interest and a run-time of 10 years.
- The plant's lifetime is considered to be 12 years, starting from 2023.
- The price for heat energy (for steam production) is assumed to be 45 EUR/MWh (natural gas).
- The electricity price for operating the plant is assumed to be 180 EUR/MWh.
- Water for the steam generator (tap water including full desalination) is calculated at 2.63 EUR/m³.
- Wastewater disposal costs for pretreated (with flocculants and chamber filter press) wastewater from the VTC is calculated at 5 EUR/m³.
- Maintenance: a flat rate of 4 % of the plant investment costs per year.
- Personnel: 3 plant operators / wheel loader drivers spread over 2 shifts (3 x 35,000 EUR/a), plus 25 % administration fee.
- Other costs (insurances, etc.): 5 % of all other costs.
- Transport costs for biochar are not calculated since the customer location is unknown.

2.8.3 Long-term economic calculations

Based on the knowledge gained, and the assumptions described, a long-term economic feasibility assessment was carried out. The result over the considered operating period of 12 years, starting with the year 2023 (first year of operation) is shown in → Table 2.4.

2.9 Conclusions

The total annual amount of beach wrack in the case study area could not be precisely determined, as the municipalities or districts collect no official figures. The absence of reliable data regarding the amount of beach wrack is surprising, as beach wrack is legally a waste under German Law as soon as it is picked up to clean the beaches.
However, even without reliable official data about the total emerge of beach wrack, all affected municipalities face a significant challenge at least during the tourist season, since the majority of beach tourists regard beach wrack as a nuisance.
The existing machines for collecting beach wrack consist of conventional construction and agricultural ones, while there is no technology specifically designed for removing large quantities of beach wrack.
The material suitability of beach wrack as a raw material for the production of biochar being a carbon-neutral substitute for fossil fuels has been proven, but with the harvesting technology currently used, the collected material often contains a high proportion of inert material (sand, clamshells, etc.), which harms the quality of the biochar produced.
An example of a production plant was developed, which would be able to treat the estimated amount

of beach wrack together with other biological waste from the Island of Rügen. An accompanying profitability calculation underlines the possibility of an ecologically and economically safe plant construction and operation. Whether this would be just as economically lucrative in other countries around the Baltic Sea without the German national carbon emissions trading law remains to be checked in each case.

			1	2	3	4	5	6	7	8	9	10	11	12
Year of operation	**unit**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**
Carbon emmission fee	[€/t CO2]	0 €	35 €	45 €	55 €	60 €	60 €	60 €	60 €	60 €	60 €	60 €	60 €	60 €
Annual price increase lignite	[%/a]	0%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Price for lignite	[€/t lignite]	75 €	77 €	78 €	80 €	81 €	83 €	84 €	86 €	88 €	90 €	91 €	93 €	95 €
Price for lignite incl. Emissions	[€/t lignite]	75 €	171 €	200 €	228 €	243 €	245 €	246 €	248 €	250 €	252 €	253 €	255 €	257 €
Discount on competing prices	[%]	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Sales price for biochar	[€/t biochar]	53 €	120 €	140 €	160 €	170 €	171 €	173 €	174 €	175 €	176 €	177 €	179 €	180 €
Revenues from biochar	**[€/a]**		**836.967 €**	**976.608 €**	**1.116.400 €**	**1.190.267 €**	**1.198.214 €**	**1.206.320 €**	**1.214.588 €**	**1.223.022 €**	**1.231.624 €**	**1.240.398 €**	**1.249.347 €**	**1.258.476 €**
Annual gate-fee increase (biomass)	[€/a]		2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Gate-fee green & garden waste	[€/t biomass]	40 €	41 €	42 €	42 €	43 €	44 €	45 €	46 €	47 €	48 €	49 €	50 €	51 €
Gate-fee leftover food waste	[€/t biomass]	50 €	51 €	52 €	53 €	54 €	55 €	56 €	57 €	59 €	60 €	61 €	62 €	63 €
Gate-fee beach wrack	[€/t biomass]	50 €	51 €	52 €	53 €	54 €	55 €	56 €	57 €	59 €	60 €	61 €	62 €	63 €
Revenues from gate-fees	**[€/a]**		**816.000 €**	**832.320 €**	**848.966 €**	**865.946 €**	**883.265 €**	**900.930 €**	**918.949 €**	**937.328 €**	**956.074 €**	**975.196 €**	**994.699 €**	**1.014.593 €**
Total revenues	**[€/a]**		**1.652.967 €**	**1.808.928 €**	**1.965.366 €**	**2.056.213 €**	**2.081.479 €**	**2.107.250 €**	**2.133.537 €**	**2.160.349 €**	**2.187.698 €**	**2.215.593 €**	**2.244.047 €**	**2.273.069 €**
Annual increase (all costs)	[%/a]	0%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Financing of investment costs	[€/a]	-838.769 €	-294.988 €	-294.988 €	-294.988 €	-294.988 €	-294.988 €	-294.988 €	-294.988 €	-294.988 €	-294.988 €	-294.988 €	0 €	0 €
Heat energy	[€/a]	-222.891	-227.348 €	-231.895 €	-236.533 €	-241.264 €	-246.089 €	-251.011 €	-256.031 €	-261.152 €	-266.375 €	-271.702 €	-277.136 €	-282.679 €
Electrical energy	[€/a]	-97.200	-99.144 €	-101.127 €	-103.149 €	-105.212 €	-107.317 €	-109.463 €	-111.652 €	-113.885 €	-116.163 €	-118.486 €	-120.856 €	-123.273 €
Feed water for steam generator	[€/a]	-16.722	-17.057 €	-17.398 €	-17.746 €	-18.101 €	-18.463 €	-18.832 €	-19.209 €	-19.593 €	-19.985 €	-20.384 €	-20.792 €	-21.208 €
Waste water from VTC	[€/a]	-79.297	-80.883 €	-82.501 €	-84.151 €	-85.834 €	-87.551 €	-89.302 €	-91.088 €	-92.910 €	-94.768 €	-96.663 €	-98.596 €	-100.568 €
Maintenance costs	[€/a]	-134.000	-136.680 €	-139.414 €	-142.202 €	-145.046 €	-147.947 €	-150.906 €	-153.924 €	-157.002 €	-160.142 €	-163.345 €	-166.612 €	-169.944 €
Personnel costs	[€/a]	-105.000	-107.100 €	-109.242 €	-111.427 €	-113.655 €	-115.928 €	-118.247 €	-120.612 €	-123.024 €	-125.485 €	-127.994 €	-130.554 €	-133.165 €
Administration costs	[€/a]	-26.250	-26.775 €	-27.311 €	-27.857 €	-28.414 €	-28.982 €	-29.562 €	-30.153 €	-30.756 €	-31.371 €	-31.999 €	-32.639 €	-33.291 €
Other costs (insurance, etc.)	[€/a]	-48.795	-49.771 €	-50.766 €	-51.782 €	-52.817 €	-53.874 €	-54.951 €	-56.050 €	-57.171 €	-58.315 €	-59.481 €	-60.671 €	-61.884 €
Transport costs	[€/a]	0	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
Total costs	**[€/a]**	-838.769 €	-1.039.747 €	-1.054.642 €	-1.069.835 €	-1.085.332 €	-1.101.139 €	-1.117.262 €	-1.133.707 €	-1.150.482 €	-1.167.591 €	-1.185.044 €	-907.857 €	-926.014 €
Annual surplus	**[€/a]**		**613.220 €**	**754.287 €**	**895.531 €**	**970.881 €**	**980.340 €**	**989.988 €**	**999.829 €**	**1.009.867 €**	**1.020.106 €**	**1.030.550 €**	**1.336.190 €**	**1.347.056 €**
Cumulative surplus	**[€]**		**-225.549 €**	**528.738 €**	**1.424.269 €**	**2.395.150 €**	**3.375.490 €**	**4.365.478 €**	**5.365.307 €**	**6.375.175 €**	**7.395.281 €**	**8.425.831 €**	**9.762.021 €**	**11.109.077 €**
Treatment costs per t of biomass (without consideration of gate-fee and biochar sale)			-55 €	-56 €	-56 €	-57 €	-58 €	-59 €	-60 €	-61 €	-61 €	-62 €	-48 €	-49 €
Overall treatment costs per t of biomass with consideration of gate-fee and biochar sale			32 €	40 €	47 €	51 €	52 €	52 €	53 €	53 €	54 €	54 €	70 €	71 €

Table 2.4 long-term economic calculations

Case study 3: Beach wrack as a compost material in landfill bio-covers (Wracover)

Authors: Guizani S.H., Busk T., Aldag S., Quintana C. O.

Case study partner: Køge Municipality. Collaboration with University of Southern Denmark and Hanseatische Umwelt CAM GmbH

Location of the case study: Køge Bay, Denmark

Aim of the case study: to test if compost made from beach wrack can be used to mitigate methane emissions from a landfill.

Test/research done: A biocover made from compost was installed at the Tangmoseskoven landfill, and methane mitigation was measured. Beach wrack compost was tested in a laboratory for compliance with standards for use in a biocover.

Staff involved: Sara Hillbom Guizani, Jacob Skjødt Nielsen

3.1 Location of the case study

The case study area is situated in Køge Bay, located in Eastern Zealand, Denmark, facing the Baltic Sea (→ Fig.3.1). Køge Municipality owns and manages two natural beaches: North Beach and South Beach (see Fig. 3.2). The total length of the managed beach is around 900 m. The management consists of regular cleaning of the beach during spring and summer seasons (see below section 2.2). The total coastline of Køge Municipality is around 12 km.

A discontinued landfill is located close to the Northern beach and marina in Køge Municipality. It is now a recreational area with a forest cover called "Tangmoseskoven" (see Fig. 3.3).

Køge Municipality has through the CONTRA project tested if beach wrack compost can be used at this discontinued landfill to mitigate methane emissions from the buried waste. The landfill has an area of around 10,000 m². A biocover, made with green cut material from gardens and parks, with an area of 1,200 m² was installed there to mitigate methane emissions.

3.2 The effect of beach wrack in Køge Municipality

The geographic location of the bay, wind conditions, shallow waters, and large seagrass meadows make the beaches in Køge Municipality prone to the accumulation of beach wrack. In 2017 and 2018, the managed beaches in Køge Municipality received on average 1,400–1,800 tons of beach wrack (wet weight). However, the yearly variations are high, local beach cleaning authorities have recorded as much as 14,000 tons in one year. The neighbouring municipalities along Køge Bay have similar high variation records in the amounts of beach wrack.

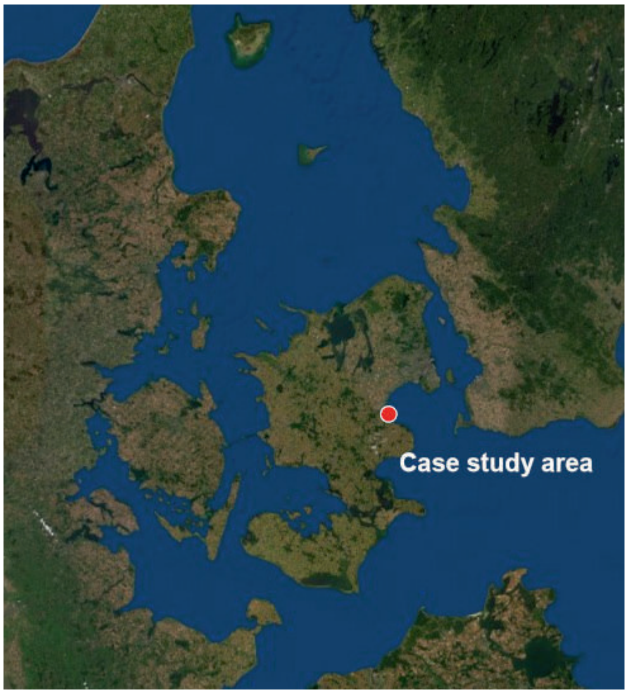


Figure 3.1 Location of case study 3 (CS3) area at the coast of Eastern Zealand, Denmark.

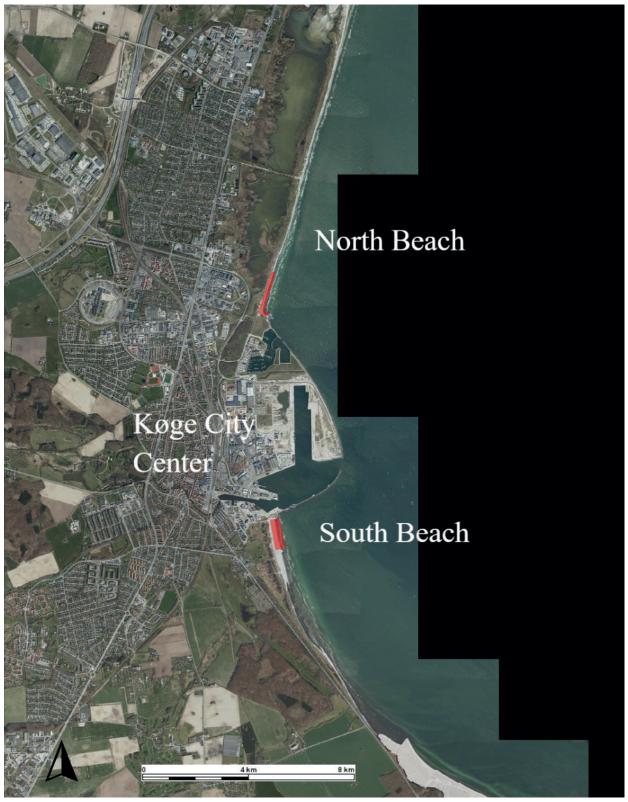


Figure 3.2 The areas (b) along the North and South Beach in Køge Municipality, where beaches are managed.

The samples collected by CONTRA project partner, University of Southern Denmark, from the managed South Beach in Køge in April–December 2019 show that dry weight in kg/m^2 of beach wrack ranges from approx. 25 kg to 380 kg per month. The species *Zotesra marina, Cladophora sp., Ceramium sp.,* and *Chaetomorpha sp.* are the most frequent macrophytes in relation to the total biomass (wet weight). → Figure 3.3 exemplifies how significant the amounts of beach wrack can be in Køge Municipality. The beach wrack creates a physical barrier between the beach visitors and the sea, making it difficult for them to go for a swim. Furthermore, beach wrack may give off a foul smell due to the microbial decomposition of the organic material. This happens, when torn off pieces of filamentous brown algae (*Pilayella litorallis*) accumulate in the water's edge. The problems with smell from these torn brown algae, also known in Danish as "fedtemøg", are a common problem throughout the coastal municipalities along Køge Bay. The smell is a great nuisance for residents and guests, who complain to the municipality if they think beach cleaning is insufficient.
Køge Municipality runs beach cleaning operations to keep the beaches free of beach wrack for tourists and residents and to avoid bad smells. The beach is cleaned every day from the 1st of May to the 30th of September for litter and beach wrack. Beach wrack is most commonly piled short-term, and the pushed back into the sea when the current allows it. This beach cleaning has a cost for the municipality. Due to the large amounts that wash up on the beaches of Køge Municipality, local authorities see beach wrack as a potential resource and are therefore interested in exploring recycling methods.

3.3 The tested technology

3.3.1 Biocover in Tangmoseskoven

In 2015 emission levels were measured in Tangmoseskoven forest showing methane emissions from the buried waste with certain hotspots with high emission levels. A technology to mitigate these emissions using compost is called a "biocover" (see Fig. 3.4).
Biocover is a technology that has been in use on several landfills internationally and in Danmark [Scheutz et al., 2014]. In 2014–2020 the Danish government financially supported experiments with biocovers on Danish landfills to mitigate emissions. The biocover in Køge Municipality is one of these experiments, contributing to the knowledge of this technology's mitigation potential. Biocover technology uses methane-oxidizing microorganisms found in compost to convert methane emissions from landfill waste to CO_2 and water [Kjeldsen and Scheutz, 2016]. Methane is a gas which has a

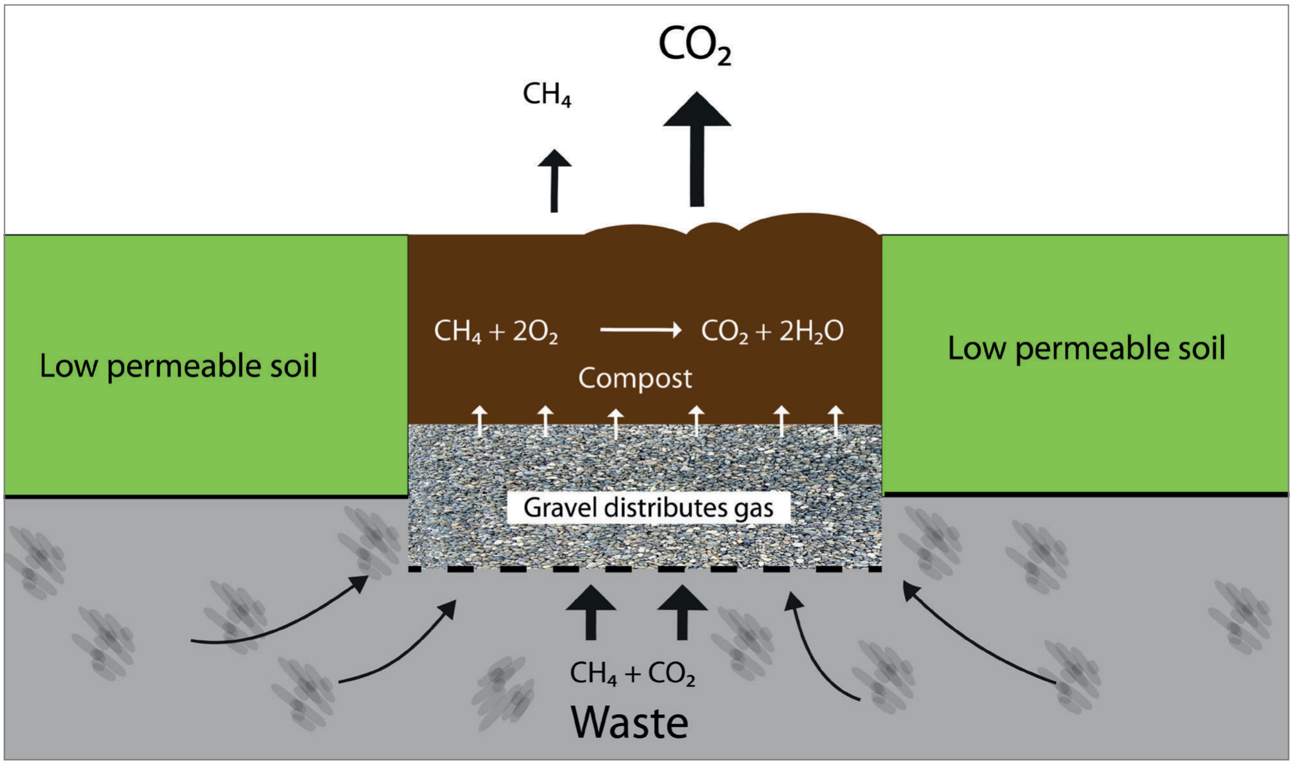


Figure 3.4 Biocover "window" system (after [Kjeldsen & Scheutz, 2014])

Figure 3.3 North Beach in Køge Municipality, May 2019

greenhouse effect 25 times larger than CO_2, and a biocover, therefore, contributes to decreasing the landfill's total greenhouse effect [Tværministriel Arbejdsgruppe, 2013].

A biocover consists of a gas-dispersal layer made up of gravel or crushed concrete placed over the landfill waste. A compost layer is added on top, either on the whole landfill or in "windows". As the original cover layer is often relatively impermeable soil, the landfill gas will migrate towards the biocover, where it will be converted to CO_2 (see Fig. 3.4). The proposed project in Tangmoseskoven included three biocover windows with a total area of 1,200 m² and plugging of five boreholes of aprox. 30 cm in internal diameter. The project was estimated to have the potential of reducing methane emissions by 4 kg methane/hour for the area of Tangmoseskoven [NIRAS, 2016]. Tangmoseskoven is approx. 147,000 m².

A biocover was established in Tangmoseskoven in March 2020.

Due to challenges described in sections 3.5 and 3.6, this biocover was made using compost produced from a mixture of garden waste from households and parks according to the standard for use in biocovers [The Danish Environmental Protection Agency & DTU, 2018]. The compost used in this biocover did not include any beach wrack. Beach wrack compost was tested separately to see if it meets the standards for compost in a biocover (see section 3.3.2 and 3.3.3).

Biocover technology is in use in landfills in Denmark [Kjeldsen & Schuetz 2011, Pedersen et al. 2012], but the technology is still new. Therefore the emissions measurements after the installation of the biocover contribute to more precise estimations of methane emissions related to landfills, which will help develop best practices for mitigating emissions.

During the project planning period, two out of the three suggested biocovers were taken out of the project for reasons explained in section 3.5. The mitigation potential of the project, therefore decreased to 3.4 kg methane/hour for the area of Tangmoseskoven according to estimations.

Figure 3.5 The discontinued Køge Landfill – "Tangmoseskoven" and the biocover. The biocover is shown in red.

Measurements of methane emissions in Tangmoseskoven in September 2020 [FORCE Tehcnology, 2020] showed a decrease by 15 kg methane/hour compared to baseline emissions recorded in 2015 [NIRAS, 2015][1], namely from 17.2 kg methane/hour down to 2.2 kg methane/hour.

Several factors could affect this measurement, such as weather, temperature, atmospheric pressure, variations in methane production and screening methods [NIRAS, 2015; NIRAS, 2016; FORCE Technology, 2020]. Additionally, the baseline measurements were made in 2015, and thus the production of methane from the waste may have decreased over time. However, the decrease in methane emission for the area of Tangmoseskoven from 2015 to 2020 is significant (87%). Thus indicating that the biocover including the plugging of the boreholes was effective in reducing methane emissions. Other studies have showed similar large reductions in emissisons after the establishment of a biocover [Pedersen et al., 2012]. It is estimated, based on a previous experiment, that the biocover itself is responsible for the reduction of approx. 60% of these emissions reductions and the plugging of boreholes is responsible for the remaining 40%[2].

3.3.2 Beach wrack compost

The purpose of this case study was to test the potential of using composted beach wrack in a biocover for landfills. A standard protocol [Kjeldsen and Scheutz, 2017, Table 2] was developed for the use of compost in a biocover.

In a study of compost samples from 13 Danish compost plants, it was concluded that, if intending to use compost made from any other material than garden waste, the material must be tested for use as a biocover against standards. It is essential for a biocover that the compost has an acceptable methane oxidation rate [Olesen et al., 2017]. The study of 15 compost samples, made from green cut waste concluded that the highest methane oxidation rates were from a compost, which had either been sieved on a fine sieve >15 mm or had composted over six months [Olesen et al., 2017].

Three samples (→ Table 3.1) of beach wrack compost were tested according to the standard protocol for biocover [Kjeldsen and Schuetz, 2017]. Two samples were from CONTRA project partner – Hanseatische Umwelt CAM GmbH. One sample was from Køge Municipality. Details of the samples can be found in → table 3.1.

3.3.3 Results of test of methane rates, respiration rates and quality criteria for compost used in biocovers

The three samples presented in → Table 3.1 were tested according to the protocol [Kjeldsen and Schuetz, 2017] for methane oxidation rate and respiration rate (→ Tables 3.3 and 3.4).

1 The baseline used here is 17.2 kg methane/hour. NIRAS 2016 used a baseline of 13.7 kg methan/hour. However, after conversations with the Danish Environmental Protection Agency it was agreed that 17.2 kg methane/hour was the most accurate baseline of total emissions.

2 NIRAS conducted an experiment concerning the temporary plugging of the 5 boreholes in Tangmoseskoven forest in 2019. The following measurement of emissions measured by FORCE Technology, showed a total methane emissions from the area of Tangmoseskoven to equal 9.9 kg/hour. This is 7.3 kg/hour lower than the baseline total emissions for 17.2 kg/hour, resulting in a reduction of 40%. The result indicates that the existing natural cover of earth and vegetation in the Tangmoseskoven forest, contributes to oxidizing methane from the buried waste in the ground. Therefore the decision was made to permanently plug the boreholes, rather than establish a biocover on top. The total methane emissions measurement was conducted at different wind directions, but the assesment is that this should not affect the results significantly. This experiment was reported on by e-mail to the Nature Protection Agency.

SAMPLE 1 BEACH WRACK COMPOST HANSEATISCHE UMWELT	
From	Hanseatische Umwelt CAM GmbH
Contains	70 % green cut material/green waste and 30 % beach wrack (sand share 50 %–70 % by weight for beach wrack)
Maturity	5 months
Description of composting process and origin of materials	Beach wrack from the Island of Poel. Collected and processed in October 2019. The beach wrack was stored until May 2020 at Hanseatische Umwelt facilities and mixed with the fresh shredded green cut material. The greencut material origin: private households and municipalities collected green cut material in the Rostock County region, in a radius of about 50 km around the Hanseatische Umwelt facilities. The green waste material was provided to Hanseatische Umwelt in April 2020. The temperature was monitored continuously. The pile was turned every 14 days. Open windrow composting, turning by the excavator. No watering.
SAMPLE 2 GREEN CUT MATERIAL COMPOST	
From	Hanseatische Umwelt CAM GmbH
Contains	100 % green cut/green waste
Maturity	5 months
Description of composting process and origin of materials	The green cut material origin: private gardeners and municipalities collected green cut material in the Rostock County region. The Hanseatische Umwelt facilities. The green cut material was provided to Hanseatische Umwelt in April 2020. The temperature was monitored continuously. The pile was turned every 14 days. Open windrow composting, turning by the excavator. No watering.
SAMPLE 3 BEACH WRACK COMPOST KØGE MUNICIPALITY	
From	Køge Municipality
Contains	33 % green cut material/green waste, 33 % beach wrack, 33 % horse manure
Maturity	Three months
Description of composting process and origin of materials	The compost pile was set up with 50 % green waste and 50 % beach wrack in August 2020. However, the beach wrack contained large amounts of sand (50 %), and the green cut material did not contain enough phosphorus (as it was mainly large sticks) to allow for quick composting. Therefore, horse manure was added in September 2020. The beach wrack was from the beach in Køge Municipality, and the green cut material from Køge Municipality. The compost pile was turned and watered weekly. The temperature of the pile was also monitored weekly.

Table 3.1 Details of tested compost samples

The accepted values for use in biocover are:
- respiration rate <48 μgO2/g material (dry weight) per hour
- methane oxidation >20μg CH4/g material (dry weight) per hour

The samples were also tested for the parameters listed in (→ Table 3.2) that are defined as quality criteria for compost to be used in a biocover according to [Kjeldsen and Schuetz, 2017].

The results show that the two samples from Hanseatische Umwelt (sample 1 and sample 2) do not meet the criteria for methane oxidation rate and respiration rate. Sample 1 met only one of the quality criteria for use in biocover, see Table 3.2. An explanation for this may lie in the low level of organic matter, due to a high percentage of sand (50 %) in the sample. High sand percentage is a result of the waves and winds mixing this material into beach wrack or the harvesting procedure, which scrapes off a few centimenters of the sand surface. The degradation processes reduced the biomass of the total sample of beach wrack compost causing a high density and low nutrient content. Additionally, the beach wrack used for sample 1 was collected from previous years, and thus the degradation was already at an advanced stage. Sample 2 fulfilled 5 out of the 8 quality criteria for use in biocover (→ Table 3.2).

PARAMETER	UNIT	ACCEPTED VALUES	SAMPLE 1 70 % GW + 30 % BW	SAMPLE 2 100 % GW	SAMPLE 3 33 % GW + 33 % BW+ 33 % HM
Dry density	g dry weight/l	260–520	812.3	632.9	153.6
Water content	g/g dry weight	0.3–0.5	0.22	0.30	2.12
Total porosity	% pore volume	60–80	37.5	51.3	88.2
Total nitrogen	mg/kg dry weight	> 5,000	4,300	7,000	11,875
NH4+-nitrogen	mg/kg dry weight	< 350	60.32	82.16	53.13
Acidity, pH	no unit	6.5-8.5	8.6	8.6	7.8
Organic matter as a loss on ignition	% of dry matter	>15 %	10.9	19.1	34.0
Dry matter	% of sample wet weight	50–80	81.8	76.9	32.0

Table 3.2: Results from samples compared to quality criteria for compost used in biocover according to [Kjeldsen & Schuetz, 2017], excluding criteria for methane oxidation and respiration. Red and green colors correspond to not fulfilled and fulfilled the biocover criteria, respectively. GW: green waste, BW: beach wrack, HM: horse manure.

SAMPLE	DAY 1	DAY 2	DAY 3	AVERAGE RATE	ACCEPTED FOR USE IN BIOCOVER
1 (container 1)	-265.95	345.06	NA	39.55	Yes
1 (container 2)	-368.07	297.71	13.67	-18.97	No
1 (container 3)	-525.25	367.77	-46.42	-67.97	No
2 (container 1)	77.67	36.81	57.97	57.48	Yes
2 (container 2)	28.4	NA	-99.19	-23.60	No
2 (container 2)	-97.34	-57.18	NA	-51.51	No
3 (container 1)	NA	NA	213.38	213.38	Yes
3 (container 2)	NA	NA	NA		Yes
3 (container 3)	231.41	NA	288.36	259.89	Yes
3 control (container 1)	NA	NA	9.94	9.94	No

Table 3.3: Methane oxidation rate in μ (measured in CH4/g material (dry weight)/hour).[3] The test was conducted according to the protocol in [Kjeldsen & Schuetz, 2017]. The methane oxidation rate (μ) accepted for use in biocover is less than 20 CH4/g material (dry weight)/hour. Red and green colors correspond to not fulfilled and fulfilled the biocover criteria, respectively.

3 Non applicable results for control samples with no added methane were removed from the table.

SAMPLE	DAY 1	DAY 2	DAY 3	AVERAGE RATE	ACCEPTED FOR USE IN BIOCOVER
1 (container 1)	59.69	NA	NA	59.69	No
1 (container 2)	NA	115.98	326.85	221.415	No
1 (container 3)	161.67	470.95	NA	316.31	No
2 (container 1)	NA	NA	NA		
2 (container 2)	70.52	63.47	59.94	64.64	No
2 (container 3)	NA	63.47	66.99	65.23	No
3 (container 1)	NA	NA	NA		
3 (container 2)	0.02	0.03	0.06	0.037	Yes
3 (container 3)	0.02	0.04	0.05	0.037	Yes

Table 3.4: Respiration rate in µg/O_2/g material (dry weight)/hour. The test was conducted according to the protocol in [Kjeldsen & Schuetz, 2017].[4] The respiration rate accepted for use in biocover is less than 48 µg/O_2/g material (dry weight)/hour.

The sample 3 from Køge Municipality fulfilled the requirements for the methane oxidation rate, and the respiration rate. Sample 3 meets 4 out of the 8 of the quality criteria for use in biocover, see Table 3.3. The results from the control sample 3 (container 1), see Table 3.3, however, indicated that the compost from sample 3 emitted methane. Active compost may stimulate methane-oxidizing bacteria, thus furthering methane conversion. However, this must not exceed the total methane oxidation rate, resulting in total methane emissions.
Sample 1, made using beach wrack, did not meet all quality criteria or have an accepted value of methane oxidation rate or respiration rate. Sample 3, made using beach wrack, did not meet all quality criteria but did have accepted values of methane oxidation rate and respiration rate. Sample 2, made from green cut waste, did not meet the quality critera or have accepted values of methane oxidation rate and respiration rate. Accepted methane oxidation rates are most significant for evaluating the ability of compost to convert methane from landfill waste. However, a compost must fulfill all criteria listed in [Kjeldsen & Schuetz, 2017] to be accepted for use in a biocover and ensure the emissions reduction effect. Overall, the results show that compost made using beach wrack can be suitable for use in a biocover as it can have an acceptable methane-oxidation rate, but more research is needed to understand its precise effect on methane-oxidizing bacteria and the proposed quality criteria.

3.4 Management-based obstacles

3.4.1 Collection, storage, and transportation of beach wrack for recycling

The Green Transition team from Køge Municipality was in an internal dialogue with the Department of Engineering and Buildings. This department is in charge of beach cleaning in Køge Municipality. The purpose was to identify guidelines for a consistent method of collecting and composting beach wrack using the machinery and facilities already available to the municipality. The technology and methods applied have proven to be challenging, as the current collecting and storing method is not properly designed for recycling of beach wrack.
The objective of the Department of Engineering and Buildings in Køge Municipality is to keep the shore clean of beach wrack and litter in the spring and summer seasons. The department collects the beach wrack in piles on site for short-term storage until it can be pushed back into the sea, when there is current. This method of collecting beach wrack can result in large amounts of sand in the beach wrack as the machines scrape sand into the beach wrack during collection. Therefore the beach wrack available to the municipality at the time was not optimal for composting.

4 Non applicable results for control samples with no added methane were removed from the table.

3.4.2 Availability of organic material and variations in beach wrack

Through the case study period, it was discovered that beach wrack must be mixed with a large portion of other organic matter (70 %), such as cuttings from gardens or parks to ensure that it will compost. The municipality manages several green areas and parks within its territory, and thus regularly collects such waste. However, the availability of green waste is limited to the spring and summer seasons. Therefore, it was not possible to make beach wrack compost in winter 2019 and early spring 2020 before establishing the biocover in March 2020.

The amount of beach wrack on Køge Municipality's beaches is highly variable. Apart from monthly variations, there are also yearly variations as mentioned above in section 2.2. In this case study, it was a challenge to plan for the collection of beach wrack and green waste simultaneously, due to variations and seasonal limitations on the availability of these materials.

3.5 Administrative/legal obstacles

3.5.1 Establishing a biocover in a coastal recreational area

Establishing a biocover in a recreational area near the coast presented several challenges during the case study. The Green Transition team applied for permissions, as well as altered the designed project based on the requirements of the Danish Coastal Authority, the Danish Environmental Protection Agency, the Department of Environment, and the Department of Engineering and Building in Køge Municipality.

The Danish coast is regulated by the National Nature Protection Act, which upholds the coastal protection line. The coastal protection line is legislation that ensures that no changes are made to the Danish coast within 300 meters from the water's edge. It was therefore necessary to apply for a dispensation from the Nature Protection Act to establish a biocover in Tangmoseskoven. Dealing with a recreational area, it was also necessary to seek permission from the municipality. The municipality had several requirements to be incorporated into the project to ensure that the construction of the biocover did not damage the recreational area or introduce any invasive species through the compost. The municipality also set requirements for testing the soil at the landfill in Tangmoseskoven to ensure that contaminated soil was not brought to the surface, where it might get in contact with those visiting the area.

The precautions that were required by the municipality to construct the biocover without damage to the recreational area meant that one of the three biocover windows was removed from the project. The second biocover window was also removed, as it was discovered that the municipality had plans to pave over this area in the future.

3.5.2 The use of beach wrack as a natural resource

The case study has shown that the beach owner, such as the municipality, is allowed to remove or let others remove beach wrack from the shore. Beach wrack is not explicitly regulated by Danish law. However, if intending to sell or give away the beach wrack, as a soil improvement product, requirements for storing such products will have to be met, and requirements for use as soil improvement must be met and proven through testing, for instance a limit on the presence of heavy metals (Cadmium). For large scale composting or storage of beach wrack, this can be an obstacle, adding further costs.

3.6 Proposals for potential solutions to beach wrack recycling

3.6.1 Biocover as a recycling option

The case study demonstrated that a biocover with green waste that has been composted according to the recommended standard for biocovers [The Danish Environmental Protection Agency & DTU, 2018], is effective in reducing methane emissions from a landfill. Compost made with 30 % beach wrack has a potential to fulfil the criteria for use in a biocover. However, the % of sand was critical and the suitability of beach wrack compost may depend on the composting process, organic material and the species composition of the beach wrack. More tests are needed to determine when beach wrack compost can be used in a biocover.

3.6.2 Cooperation with local actors

The case study has demonstrated that, if intending to use composting as a recycling method, it is necessary to locate enough organic material to co-compost with the beach wrack. In the case study example, a total of 1,200 m³ of compost material was needed for 1 biocover window. This amount will vary according to the size of the landfill and biocover. A municipality may have access to some

amounts of other organic material, but it may also be beneficial to cooperate with waste management companies with access to more organic material that can be co-composted with beach wrack.
Methods and machinery for collecting beach wrack used by municipalities are not optimal for later beach wrack recycling. One possible solution is to cooperate to a higher degree with local actors, such as farmers with land near the sea, private beach cleaning companies, or private-public waste management companies, who have available machinery and space to produce beach wrack compost.

3.6.3.Other options for recycling beach wrack

The case study demonstrates that composting is one method of reusing beach wrack. However, high amounts of organic material are needed to compost the beach wrack. There may be other methods where a higher percentage of beach wrack is used directly in a new product. On the other hand, composting may be a possibility for using mixtures of beach wrack that are not easily recyclable into higher-value products.

3.6.4 More knowledge on seasonal beach wrack variations

The high seasonal and annual variations in the amount of beach wrack biomass make it more challenging to plan the collection and composting. Additionally, the production of compost needs to be timed to the availability of organic waste. More knowledge on the patterns in seasonal variation of beach wrack amounts is needed if intending to have a reliable supply of any beach wrack product. Similarly, knowledge on the seasonal species composition of the beach wrack is relevant for the products that only use components of beach wrack, such as eelgrass. The CONTRA project and its results are a good example of projects providing relevant knowledge on seasonal beach wrack variations at Baltic Sea beaches.

3.7 Conclusions

The biocover composed by 100 % green waste, which met the compost standard [The Danish Environmental Protection Agency & DTU, 2018] was effective in reducing methane emissions from the old landfill in Tangmoseskoven. In the case study, the biocover along with the plugging of 5 boreholes reduced methane emissions at the landfill by 87 %.
Tests of compost with 30-33 % beach wrack fraction showed that one out of two samples met the methane oxidation criteria required for application as a biocover [Kjeldsen & Schuetz, 2017]. These results are based on small sample size, and demonstrate that further research should be performed on which type of organic material stimulate and contribute to the presence of methane-oxidizing bacteria.
The case study shows that beach wrack can be composted as a recycling method, although it will make up only 30-33 % of the total compost amount. This recycling option may be particularly applicable if beach wrack is mixed, and cannot be separated into macroalage and eelgrass fractions for direct reuse.
The case study has also shown that it can be difficult for a municipality to bear the cost of collection, storage, transportation and composting of beach wrack. Therefore municipalities chose the easier option of collecting beach wrack short-term, before pushing it into the sea. Additionally, the municipality may lack facilities and machinery for the task of carefully collecting beach wrack, so it is free of sand. They may also lack space and facilities for composting. For this reason, it would be beneficial to cooperate with other municipalities, local waste management companies, and private beach cleaning companies for recycling beach wrack through composting.

Case study 4: Assessment of beach wrack applicability for dune restoration measures (Wrack4coast)

Authors: Gorbunova J., Domnin D., Domnina A., Chubarenko B., Rylkow O., Mayorova Iu.

Case study partner: Atlantic Branch of P.P.Shirshov Institute of Oceanology of Russian Academy of Sciences (ABIORAS) in cooperation with National Park "Curonian Spit", Associated Partner (AP)

Location of the case study: Kaliningrad Oblast, Russia

Aim of the case study: To test if beach wrack can be used for coastal protection measures (for the planting of greenery and sand retention in wooden cells)

Test/research done: The experiments were focused on the use beach wrack based compost in coastal erosion protection measures: (a) to promote plant growth and root stability for artificially planted greenery on the backside of the coastal dune, and (b) using the bach wrack as initial filler for the wooden structures on the seaward side of the dune to facilitate a natural accumulation of beach sand and rooting of sand-holding grasses.

Staff involved: Julia Gorbunova, Boris Chubarenko, Dmitry Domnin, Anastasia Domnina, Alexey Grave (all ABIORAS), Oleg Rylkow, Iuliia Mayorova (both AP)

4.1 Location and geographical description (D. Domnin)

The Kaliningrad Oblast is the most western, exclave region of the Russian Federation (→ Fig. 4.1). From the west, it is washed by the Baltic Sea, has two inland marine transboundary waterbodies – the Curonian and Vistula Lagoons. The lagoons are separated from the sea by the sandy Curonian and Vistula Spits, respectively. In the south, the Kaliningrad Oblast has a border with Poland, north and east – with Lithuania. The area of the Oblast (together with the lagoons) is 15.1. km². The length of the coastline is 145 km, of which the spits occupy 72 km. The Kaliningrad Oblast suffers from coastal erosion and cliff abrasion (→ Fig. 4.2) due to storm activity. During the winter storms, seashores erode, and during summer lulls, sandy beaches increase. The "hard" shore protection structures are used to protect the Sambia Peninsula shores, and the "light" ones are applied to preserve the sandy spits.

Thus, several sites were identified for the case study of beach wrack in the Kaliningrad Oblast (→ Fig. 4.1): the area on the Curonian Spit where artificial planting using beach wrack–based compost was made; the area on the Vistula Spit to use

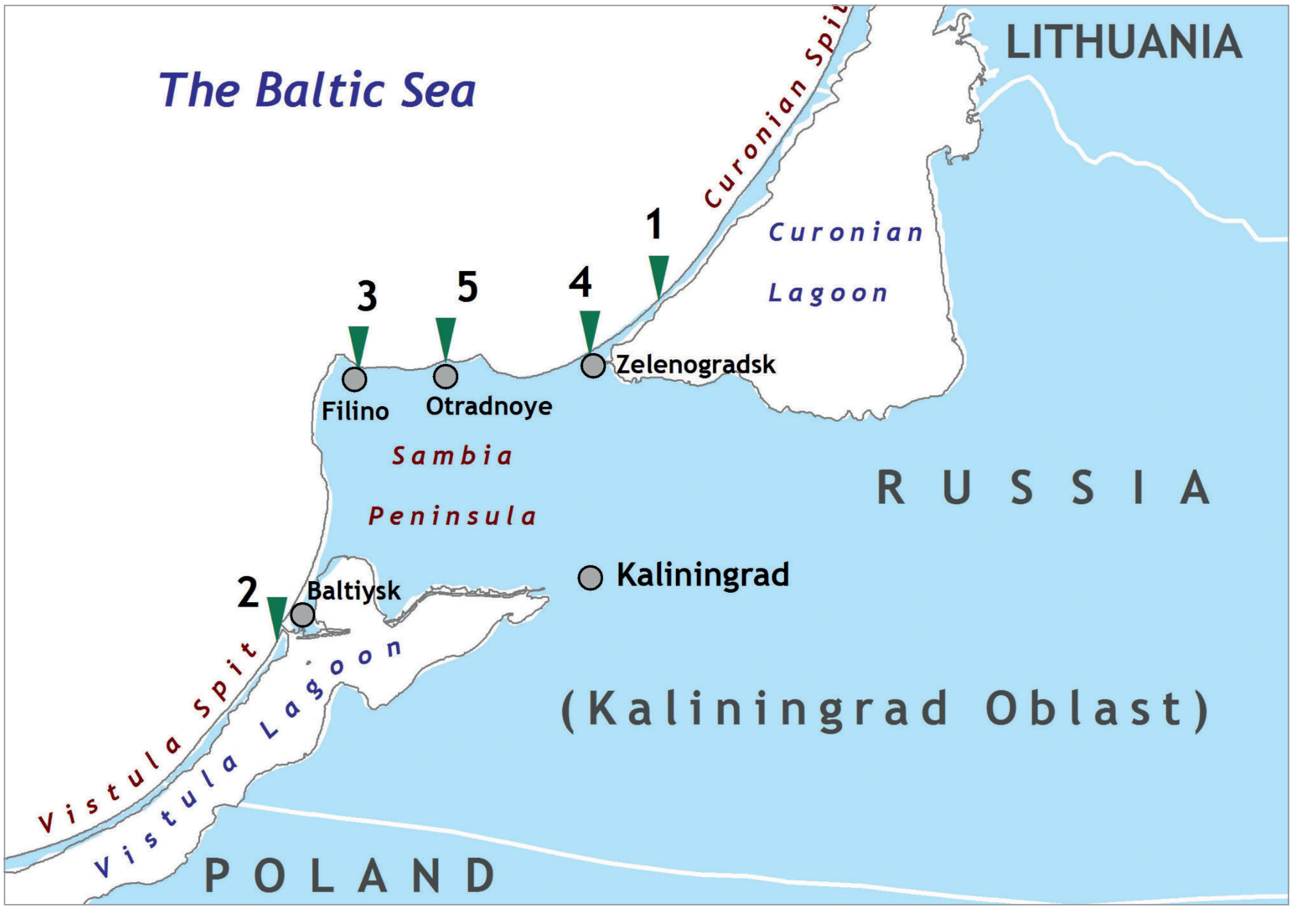


Figure 4.1 Location of the case study sites in the Kaliningrad Oblast. 1 – the experimental site for beach wrack use for greenery planting; 2 – the experimental site for beach wrack use for sand accumulation constrictions; 3 – the site for regular beach wrack monitoring and sampling on an unmanaged beach; 4 – the site for regular beach wrack monitoring and sampling on a managed beach; 5 – the site for beach wrack residence time remote monitoring (webcam).

Figure 4.2. Coastal erosion (the western part of the Curonian Spit, Kaliningrad Oblast, Russia, March, 2020), photo: J. Gorbunova.

beach wrack for sand trapping structures; several sections on the northern shore of Sambia Peninsula where observations were made (Filinskaya Bay, beaches in Zelenogradsk and Otradnoe).

4.2. Description of the case study sites (J. Gorbunova)

The experimental implementation of case study 4 (Wrack4coast) was carried out on the two spits of

Figure 4.3. Experimental sites for beach wrack use for coast protection measures: (a) for greenery planting, (b) for sand accumulation constrictions, photos: (a) O. Rylkow, (b) B. Chubarenko.

Kaliningrad Oblast. The Experimental site for beach wrack use for greenery planting (→ Fig.4.3) was situated in the western part of the Curonian Spit in the Federal State Budget Institution "National Park "Curonian Spit". The Experimental site for beach wrack use for sand accumulation constrictions (→ Fig.4.3) was situated in the eastern part of the Vistula Spit on the Kosa settlement beach.

Regular beach wrack monitoring and sampling were carried out on the beaches of the northern part of the Sambia Peninsula (→ Fig. 4.4): unmanaged ones – in the Filinskaya Bay and managed ones – on the eastern part of the Zelenogradsk beach. The site for the beach wrack residence time remote monitoring by a webcam was in the western part of the Otradnoye beach (→ Fig. 4.4), and on the northern part of the Sambia Peninsula.

4.3 Beach wrack effect as a natural process (J. Gorbunova)

4.3.1 The problem of beach wrack in the Kaliningrad Oblast, Russia

The problem of beach wrack is present in the Kaliningrad Oblast of Russia, South-Eastern Baltic. From time to time, large amounts of beach wrack appear in various places along its seashore. Apart from some preliminary studies, beach wrack casting's natural conditions were not studied in detail, and beach wrack cast quantities were not estimated yet [Golmanova & Volodina, 2013; Besedina & Nazarova, 2017]. VNIRO Institute scientists studied algae's washouts on the eastern Baltic coast in 1950–1956 [Kireeva, 1960], 1968–1972 [Blinova, 1971; Blinova & Kutyunis, 1973]. However, these studies were confined to Lithuania and Latvia's seashore and focused on commercial species of algae only (*Fucus, Furcellaria*). Questions about conditions and sites of beach wrack release, as well as the estimated beach wrack quantities at the seashores of Kaliningrad Oblast are still open.

4.3.2 Shore surveys and continuous visual observations

A survey of the Baltic Sea seashore within the Kaliningrad Oblast was conducted in March 2019 – August 2020. The beach wrack was recorded (measured, described and geo-referenced using GPS navigation), and sampled at two model sites (managed and unmanaged) monthly (→ Fig. 4.4) and alongshore surveys were carried out seasonally.

Monitoring of the time of residence of the beach wrack was carried out three times per day (November 1 2019 – May 14, 2020, and after August 25 2020), and five times per day (May 15 – August 25 2020) at the selected model site on the Otradnoye beach by using a web camera (→ Fig. 4.4).

4.3.3 The ways of beach wrack transformation on the beach

Beach wrack effect is a natural process in the seashore ecosystems of Kaliningrad Oblast. The further transformation of beach wrack can develop in several ways: flushing back to the sea (the most common), being covered under the layer of sand or small pebbles (also followed by flushing, in most cases), the wind-wave dispersal along the beach (→ Fig. 4.5).

4.3.4 Spatial distribution and amount

It was found out that the distribution of beach wrack was characterized by significant spatial and temporal variability. In general, large amounts of beach wrack were observed on the northern coast of the Sambia Peninsula, contrasting to the western coast, Curonian and Vistula spits. The

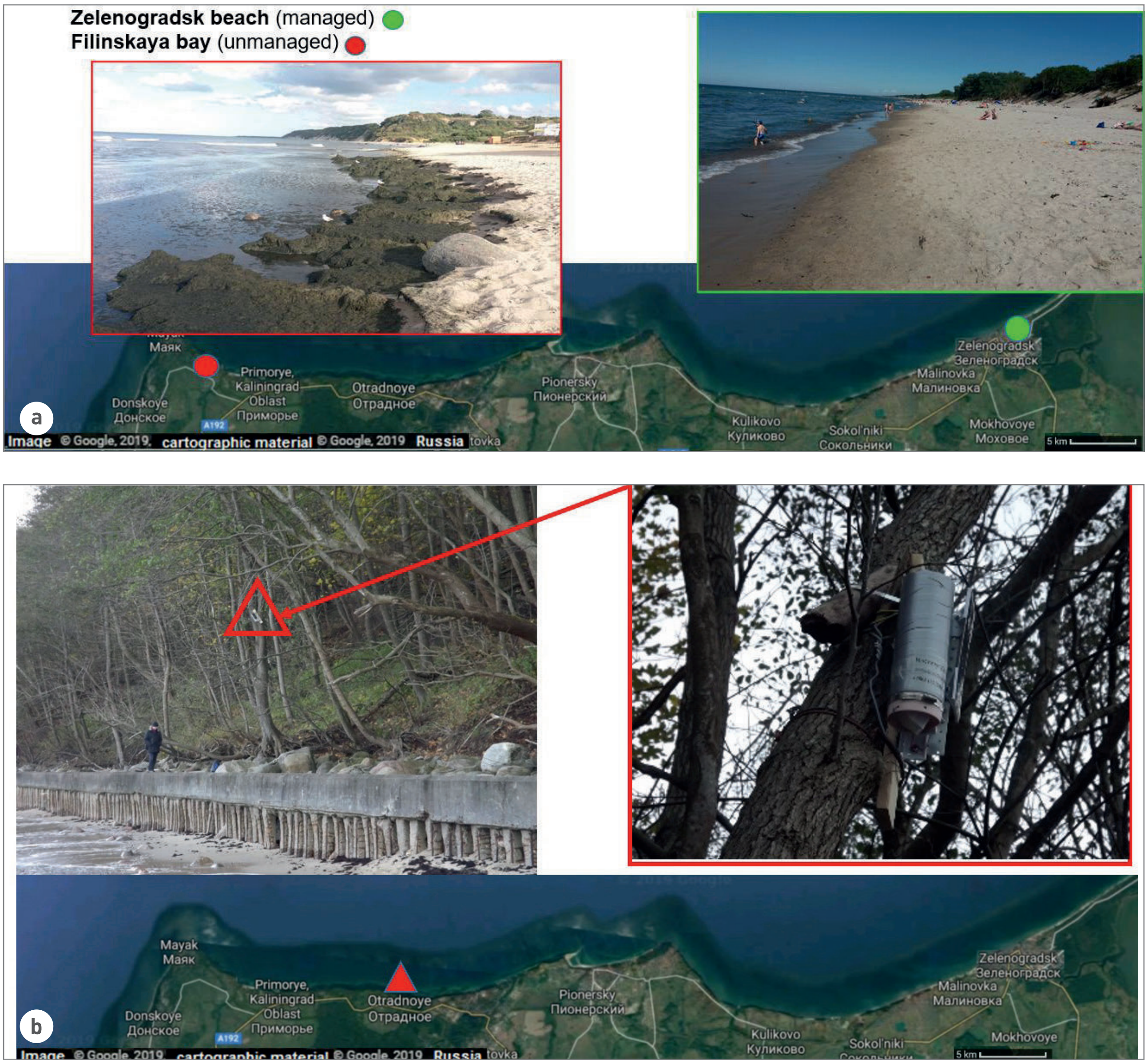


Figure 4.4. Beach wrack regular monitoring sites: (a) an unmanaged beach (Filinskaya Bay and a managed beach (Zelenogradsk), (b) a webcam (Otradnoye beach), photos: (a) J. Gorbunova, (b) A. Grave.

largest accumulations of beach wrack were local and mainly occurred near the coastline protrusions, such as capes (natural) and breakwaters, slipways, groins (human-made).

The most considerable amounts of beach wrack in summer 2019 were recorded in the area of the northern breakwater in Baltiysk; in the Filinskaya Bay (especially in the area of the slip); in the western part of the beach of Pionersky, behind the breakwater of the port; in the area of the Zaostrovie village, behind the Gvardeysky Cape; in the western part of the Otradnoye village beach; and beyond the eastern border of the municipal beach of Zelenogradsk. The most considerable amounts of beach wrack in early spring 2020 were recorded in the Filinskaya Bay area and the Otradnoye beach (→ Fig. 4.6).

4.3.5 Seasonality and composition

The composition and amount of beach wrack result from the see grasses growing disrupted and transported in near-shore waters [Mossbauer et al., 2012]. The seasonal dynamics of algae species in the composition of beach wrack were observed. beach wrack mainly contained *Rhodophyta* algae in early spring, autumn and winter, in contrast to summer, when there were also *Chlorophyta*.

4.3.6 Time of residence

beach wrack residence on the shore varied greatly and was often limited to a few days. During the observation period (November 2019 – May 2020), the residence time ranged from 22 days to less than one day, and on average was 4 days.

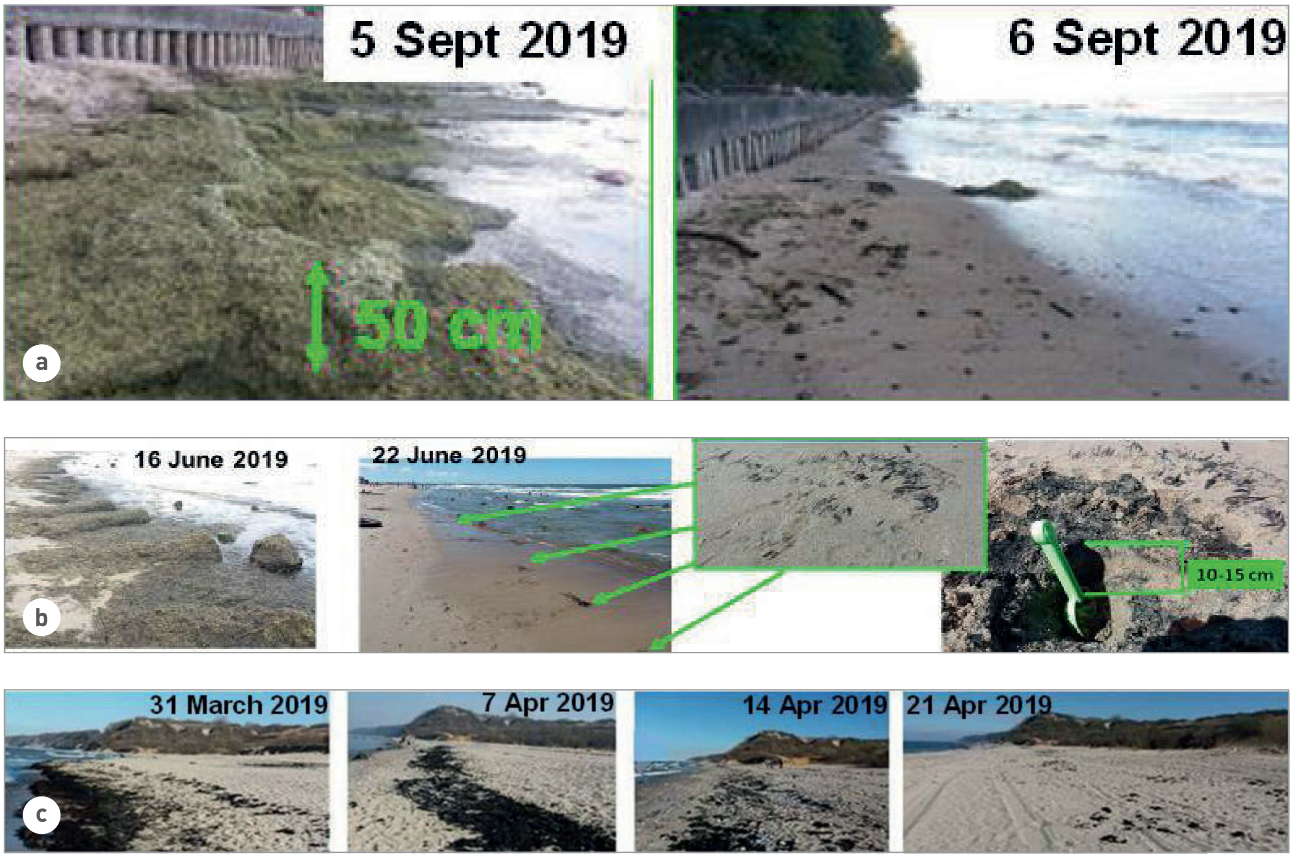


Figure 4.5. Beach wrack can undergo different transformations: flushing back to the sea (a), being covered under a layer of sand or small pebbles (b), the wind-wave dispersal along the beach (c), photos: J. Gorbunova.

The time of beach wrack residence was associated with the strength and direction of the waves, which in their turn depended on the strength and direction of the wind. The beach wrack usually stays on the beach in winds of eastern and southern directions and low wind of western directions. Flushing of the beach wrack was due to intensive winds of northern and western directions wherein the waves flooded the beach and washed away the beach wrack (→ Fig. 4.7).
Wind-wave conditions also define the appearance of the beach wrack. However, the dependence between the appearance of beach wrack and winds of specific directions and forces is less evident than the beach wrack washout from the beach.
The beach wrack's appearance on the Otradnoye beach (the northern coast of the Sambia Peninsula) was most often accompanied by winds of the eastern and southern directions and the western direction, but not very intensive. The dependence of the beach wrack appearance from the east side of the groin on the east wind was quite noticeable. Some days before the beach wrack appearance, there was often a storm happening. The literature describes the dependence of beach wrack on the strength and direction of waves and wind. West stormy wind (southwest, northwest) caused the beach wrack cast on Lithuania's coast [Blinova, 1971]. The beach wrack cast's primary condition is the sequence of two events: the drift of macroalgae to the water's edge and the subsequent rapid decrease in sea level, in which the beach wrack drifted near the shore stays on the beach.

4.3.7 Beach wrack characteristics and conclusions

As the studies have shown, the original wet weight of beach wrack is 450 kg·m-3 on average. The original wet weight of beach wrack varies greatly depending on the content of sand and small pebbles, as well as the humidity of the algae, and can reach 1,072 kg·m-3. The average sand content in the beach wrack is 39 % and can reach 87 %. Little sand content in beach wrack is rare. The situation, when sand was absent in beach wrack, was observed only once.
beach wrack contained xenomaterials, most of which were plastic (→ Fig. 4.8). The xenomaterial inclusions were in 28 % of samples; 99.9 % of them were mesoplastic, and 77 % of those were polyethylene (size 1-50 cm^2). Thus, on average 1 m^3 of

Figure 4.6. Beach wrack stock estimations, as of July 2019 (Curonian Spit, September 2019) (a) and March 2020 (b): 1 – beach wrack layer thickness more than 15 cm; 2 – beach wrack layer thickness less than 15 cm; 3 – beach wrack is absent or in a small amount (coverage with beach wrack is not continuous).

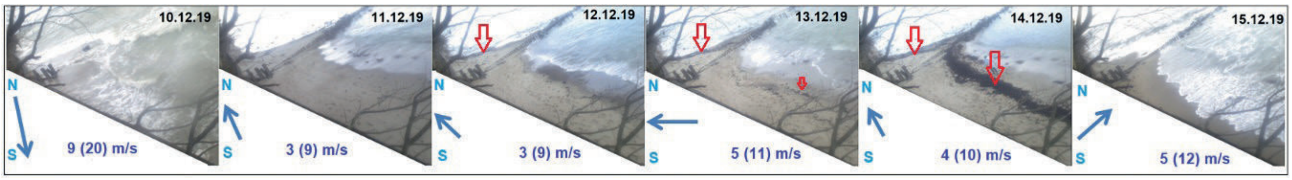


Figure 4.7. A typical example of beach wrack being cast and flushed away, due to the wind conditions (beach of the Otradnoye settlement, northern exposure of the coastline). The measured average wind direction and speed are indicated (wind gusts – in the bracket, the weather station is located at a distance of 5 km, *https://rp5.ru*).

beach wrack contained ~ 130 pieces of xenomaterial inclusions, including ~ 0.06 m² of polyethylene. The estimations show that the industrial use of beach wrack is limited by the spatial and temporal irregularity of its casts in the Kaliningrad Oblast, Russia. However, the need for beach wrack collection and utilization still exists. beach wrack can be used as an additional improver in ongoing shore consolidation activities, namely planting dune greenery, as a source of nutrients.

A possible solution could be to use the webcam observations on the potential seashore with good transport accessibility to coordinate the beach wrack harvesting activities. It is more efficient to harvest beach wrack from new casts, as after being flushing flushed back into to the sea and subsequent subsequently cast again, the beach wrack contains more sand and litter.

4.4 Estimations of areas and volume of the beach wrack cast on the shore at the model site (D. Domnin)

The webcam, temporarily installed in the Otradnoye settlement, was programmed to receive regular images, covering the beach to the west and east of the groin. Images were shot several times a day during daylight hours (at 9, 12, 15 o'clock local time). Additionally, the shooting was done at 6, 18 and 21 o'clock for longer daylight hours. The pictures show the beach and the beach wrack cast onto it (→ Fig. 4.9).

The analysis of the images was carried out in two stages. At first, the information on the beach and beach wrack cast on both sides of the groin was visually estimated, and the data was recorded in the "yes/no" table. Next, only the images with beach wrack were selected, and the areas covered with beach wrack were estimated.

The digitization of the cast boundaries introduced the main error in determining the area of beach wrack in the webcam image. The error was also affected by the beach wrack cast's continuity – the error increases with dispersed spots of the cast. The error value was +/- 10 %.

From November 1, 2019, to May 31, 2020 (213 days), the beach was nearly always in place from both

Figure 4.8. Typical inclusions of mesoplastic in the beach wrack, photos: J. Gorbunova.

Figure 4.9 The original image obtained from the webcam installed near the Otradnoye sett., the Kaliningrad Oblast (Russia).

sides of the groin. And there was a small asymmetry – the beach was attached for 160 days to the west of the groin, and for 154 days – to the east of it. The beach was absent for 53 and 59 days, respectively (→ Fig. 4.10)

Beach wrack appeared only if there was a beach in place. Situations, when the beach wrack existed, but the beach was absent, were not recorded. In most cases, beach wrack appeared several days after the formation of the beach.

The largest number of days, when the beach wrack casts were on the beach, was recorded in November 2019 (more than 20 days). In December, the number of days decreased to 7, in January and February there were practically no beach wrack, and from March to May 2020, beach wrack reappeared, but less often than during 15 days a month. In fact, for all the months, when beach wrack was present on the beach, there was always more beach wrack to the east of the groin (→ Fig. 4.11).

To estimate the volume and weight of the beach wrack collected from the beach, the beach wrack sampling at the two sites (1.9 m² and 6.5 m²) were made on 07.10.2020. On the site No1, the beach wrack was mostly fresh; 120 litres were collected with a total weight of 91.3 kg. On the site No2, the beach wrack was mostly not fresh, mostly old and partially trampled, previously cast beach wrack (90 %) and a small amount of fresh beach wrack (10 %). 110 litres weighing 119.5 kg were collected from the site No2.

Experimental data shows that the volume of wet beach wrack with sand material gathered from one linear meter of the waterfront from site 1 (fresh beach wrack) and 2 (not fresh beach wrack) was 120 and 110 litres respectively, that gives the mass of 91.3 and 119.5 kg of dry beach wrack with sand. The amount of material gathered from 1 m² of the beach wrack cast from site 1 (fresh beach wrack), and 2 (not fresh beach wrack) were 63.2 and 16.9 litres per m² or 48.1 and 18.4 kg per m². Thus, we may conclude that the specific volume of the fresh beach wrack (after its gathering for transportation) is 3.7 times higher than the one of the not new and caked beach wrack, while the specific mass of the fresh beach wrack is 2.6 times bigger than of the not fresh beach wrack.

4.5 Beach wrack for the planting of greenery, Curonian Spit (J. Gorbunova, O. Rylkow, Iu. Mayorova)

The implementation of case study 4 was carried out in the National Park "Curonian Spit" in collaboration with the Institute of Oceanology RAS.

4.5.1 Historical and environmental aspects

Curonian Spit (UNESCO World Heritage Site) is a sand-dune spit that separates the Curonian Lagoon from the Baltic Sea. The destruction of the foredune wall leads to the threat of the flooding the forest located on the Spit [Karmanov et al., 2018]. Planting of greenery is a measure used on the Curonian Spit since long ago. The foredune of the Curonian Spit is mostly a human-made construction mounted in

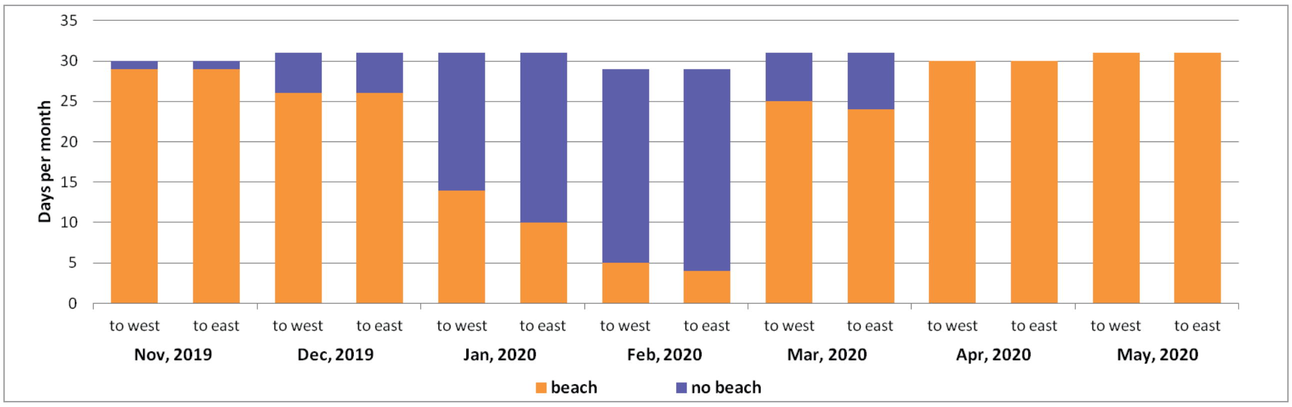


Figure 4.10. Monthly variations of beach presence to the west and east from the groin from November 1, 2019, to May 31, 2020.

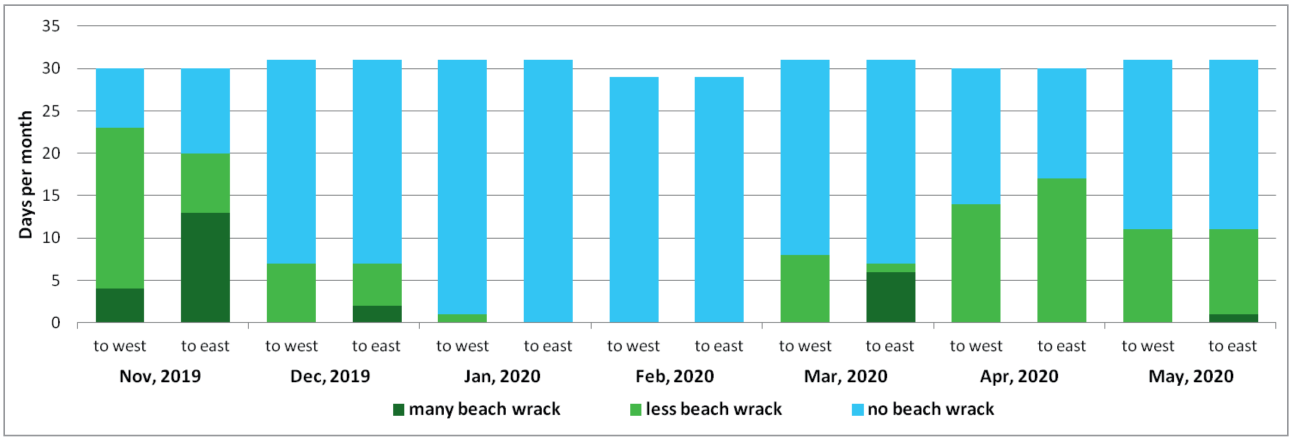


Figure 4.11. Monthly variations of the beach wrack presence to the west and east from the groin in the period from November 1, 2019, to May 31, 2020

XIX with successive use of wooden structures and greenery [Curonian..., 2008]. By analogy with the historical use of algae to fertilize soil [McHugh, 2003], greenery planting could be significantly more effective with beach wrack as a source of nutrients. It should be similar to a natural process. Algae thrown ashore are a component of fertilizer for dune vegetation in the process of coastal dune formation [Walter, 1975]. With this method, xenobiotic substances will not be brought into the environment, since algae from beach wrack are an inherent part of the coastal ecosystems.

4.5.2. Substantiation of the methodology and selection of plant species

Agrarian and climatic conditions on the open sandy surface of the dune wall are harsh. It is practical to use fertilizers that stimulate seedlings' growth and survival to increase vegetation plantings' survival rate. That is why the use of beach wrack as a natural fertilizer looks promising.

Organic fertilizer from beach wrack was obtained by composting with methods similar to those used for planting green plants [Druzhinina et al., 2016; Tarkhanova & Lobkova, 2015; Vasiliev, 2015]. For that, a wooden container was used. The composted mass of beach wrack was stirred to aerate it and prevent putrefactive processes. The consistency of organic matter determined the duration of composting.

Studies of the beach wrack compost's effectiveness were done by standard methods accounting for the morphological parameters and survival rate of seedlings. The planting of greenery was carried out at the experimental and representative sites to identify the differences' significance.

There are harsh habitat conditions in the dune wall – strong winds, unstable sand soils, periodical salinization by sea spatters. Only some species of plants with adaptive properties can exist under such conditions. The plant has to be resistant to sanding, exposure of roots, and recreational loads as well.

Berberis vulgaris was chosen for planting as it is tolerant of low soil humidity and low temperature. This specie of barberry is characterized by an early start and late completion of the growing season, and it reaches a height of 1.5-2 m under favourable

ACTIVITY	PERIOD
Supplementary scientific work – methodology and data analyses.	January 2019 – December 2020
Preparation of seed material – harvesting and planting of seeds.	October 2018
Cultivation of (watering, weeding, loosening) the planted seedlings.	April – September 2019
Construction of a compost container.	September 2019
Beach wrack harvesting and transportation.	October, November 2019
Beach wrack composting with mixing (aeration) and monitoring of the environmental conditions (temperature).	November 2019 – May 2020
Planting and cultivation of the yearlings at the case study sites.	May – September 2020
Inventory of the yearlings (survival and morphological parameters).	June, September 2020

Table 4.2. Schedule of experimental activities

conditions. Resistance to this plant's anthropogenic impact is ensured by thorns on the branches and a robust root system, horizontally diverging below summer drying horizon.

4.5.3. Schedule of experimental activities

The schedule of the main stages of the experiment is presented in → Table 4.2.

4.5.4 Beach wrack harvesting and transportation

In the Kaliningrad Oblast, beach wrack casts are characterized by their spatial and temporal irregularity (see Chapter 4.3.4 and 4.3.5), which causes significant difficulty for their harvesting. To solve this problem, a "quick response" method was used based on seaside monitoring results. A small beach wrack cast occurred in October 2019 on the Curonian Spit close to the case study site (→ Fig. 4.12 a,b). It was convenient and cost-effective in terms of transportation costs. However, the amount of beach wrack harvested on the Curonian Spit was not enough for the experiment's needs. Beach wrack casts are very rare on the Curonian Spit. Therefore,

Figure 4.12. Beach wrack harvesting by hand (a) on the Curonian Spit (b) and in the Filinskaya Bay (c). Photos: (a), (b) O. Rylkow, (c) J. Gorbunova.

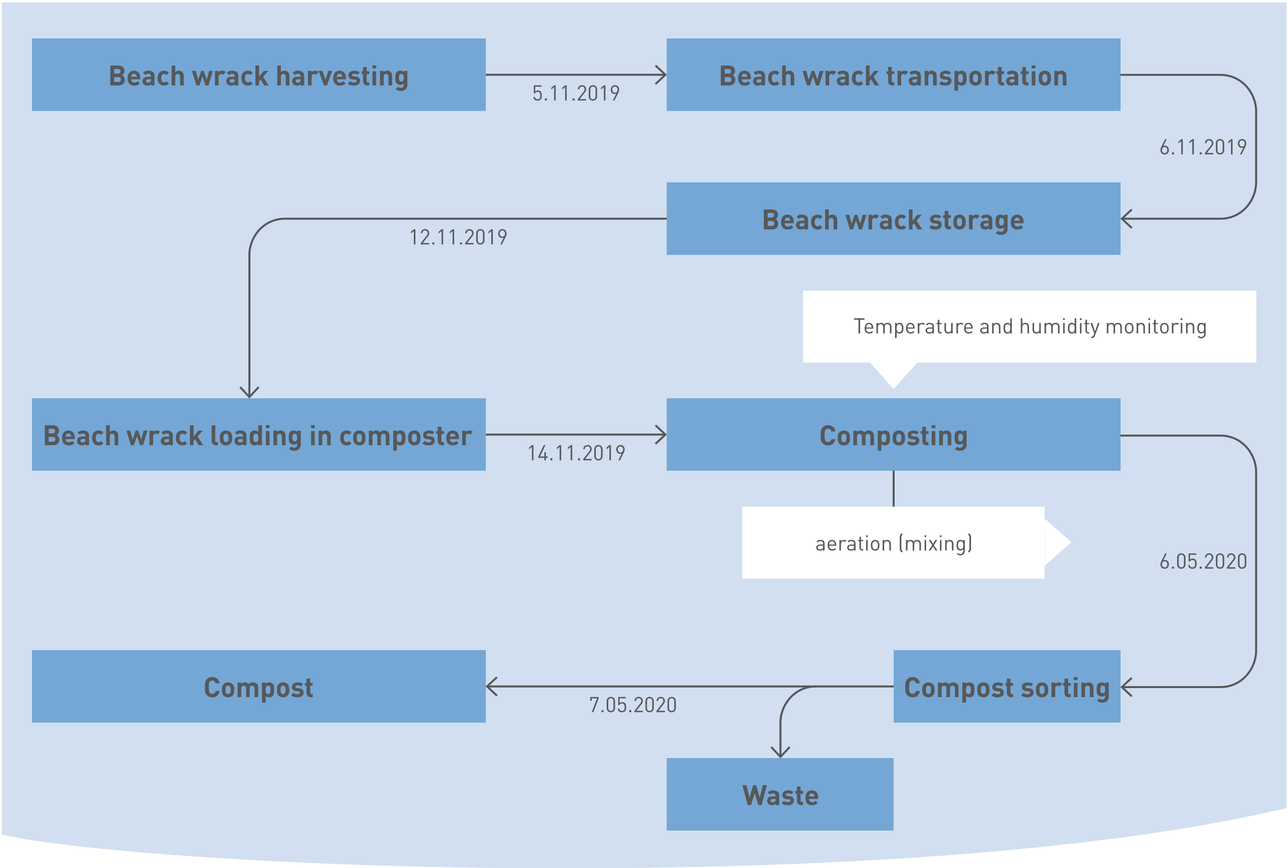


Figure 4.13 The beach wrack composting scheme.

the required amount of beach wrack was harvested in the Filinskaya Bay (→ Fig. 4.12 c) located at 50 km from the Curonian Spit, in November 2019. In this part of the seashore, large amounts of beach wrack often appear (see Chapter 4.3.4), and there is good transport accessibility to this seaside area.

Beach wrack was harvested by hand (→ Fig. 4.12 a). Separation of impurities (sand, land vegetation, garbage, etc.) was not done. There was very little garbage in the harvested beach wrack. A total of 500 kg of beach wrack were harvested, and about 90 % of that amount was from the Filinskaya Bay. The algae's dominant species were *Furacellaria lumbricalis* (Filinskaya Bay) and Cladophora sp. (Curonian Spit).

4.5.5 Beach wrack composting

The scheme used for beach wrack composting is shown in Fig. 4.13. The experimental composting site was a square wooden container (2x2x1 m) placed on low brackets to improve aeration. The container sides were lined around the perimeter with packages of hay to prevent freezing in winter. The compost container was constructed outdoors on sandy soil without any special drainage.

Beach wrack was placed in the compost container's central part without tamping and covered with hay (→ Fig. 4.14). Composting process was carried out from December 2019 to May 2020. No additional irrigation was done. The surrounding temperature was 0°C– +7 °C in winter. Aeration of the compost mass was carried out by stirring it in December 2019 (→ Fig. 4.14). A gradual temperature decrease of compost mass was observed from 29 °C to + 10–12 °C in 8 weeks.

As a result, in early May 2020, the compost was loose, crumbly, with a slight ammonia smell, and dark in colour. It contained a significant amount of beach sand and no initial algae fragments.

4.5.6 Planting material

The planting material was the yearlings of *Berberis vulgaris* (→ Fig. 4.15). Seeds were harvested from wild bushes on the Curonian Spit. They were planted in October 2018. Irrigation, weeding and loosening were done during the cultivation in April–September 2019. In May 2020, The size of yearlings was 18–25 cm.

4.5.7 Case study sites description

Case study sites were placed in the dune wall section at the 15-kilometre mark on the Curonian Spit.

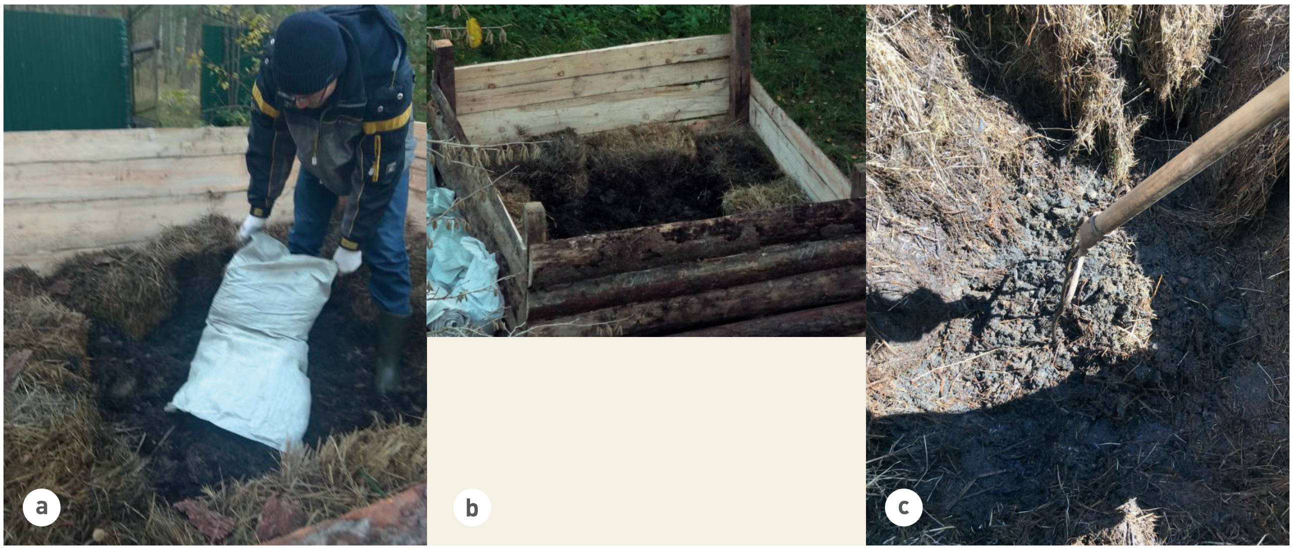


Figure 4.14. Beach wrack composting: (a) storage in the composting container (b) and aeration/stirring of the beach wrack compost mass (c), photos: (a), (b) O. Rylkow, (c) Iu. Mayorova.

Figure 4.15. Cultivation of the planting material: (a) planting of seeds and (b) barberry seedlings in May 2019, photos: O. Rylkow.

The mechanical consolidation of sand in this area was done by wooden cells (0.7 m high) in 2017–2018 (→ Fig. 4.16). The downwind slope of the dune wall was chosen for the case study. The size of the area was 5x10 m. The slope's local relief was not flat, the slope at the focus area was 15-20º and faced to Southeast. The vegetation was absent with rare exceptions of some herbs (*Corynephorus canescens, Carex arenaria, Lathyrus maritimus*).

4.5.8 Planting and cultivation

Planting was carried out in May 2020, after the seedlings' spring vegetation had started (→ Fig. 4.17). Greenery was planted at two sites: experimental and verification ones. Pits were made with a shovel (a hand drill). Seedlings were irrigated after planting. Beach wrack compost was applied at a depth of 20-30 cm at the experimental site only. Compost mass was added (under the roots) when planting [Rodin & Rodin, 2010].

4.5.9 Effectiveness of the experimental method

A photo testing method was used for the quality assessment of the beach wrack compost. Seedlings were planted at two sites: experimental and verification ones. Beach wrack compost was applied at the experimental site only. The cultivation of plants at the experimental and verification sites was done under identical conditions. The morphological parameters of the plants (length of the aboveground part), as well as the seedlings' survival rate, were determined at the end of the growing season in September 2020 (→ Fig. 4.18).

The following results were obtained: the survival rate of the plants was 83 % at the experimental site and 88 % at the verification site; the plants grew in height compared to the initial size by 52 %±3.1 % and 25 %±3.0 % respectively.

4.5.10 Business benefit analysis

A cost calculation of planting the greenery with and without compost was made. The following costs were

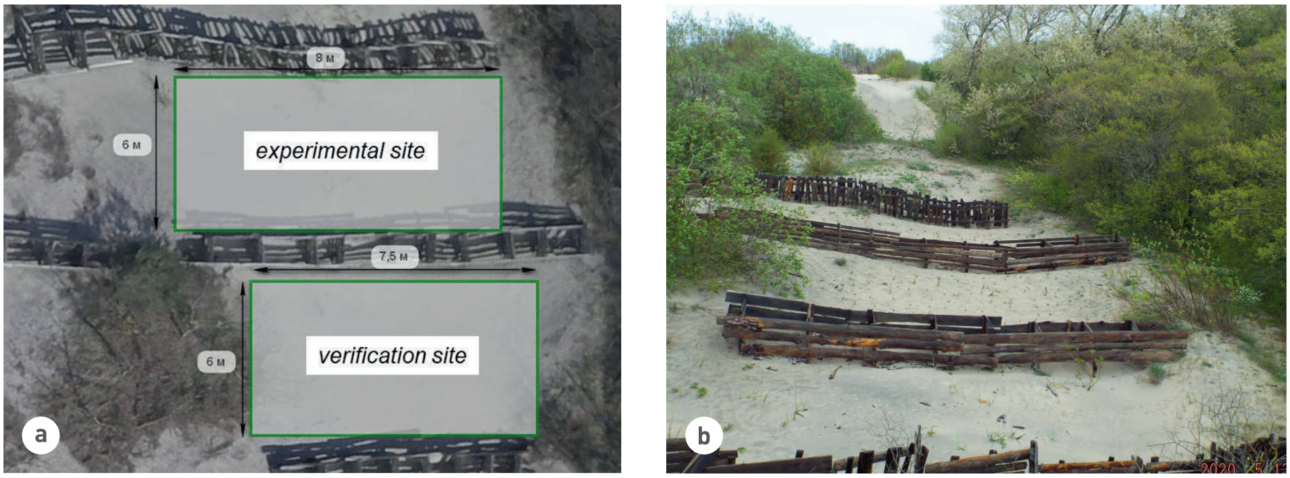


Figure 4.16. Case study sites for the greenery: (a) experimental and verification sites; (b) mechanical consolidation of sand by wooden cells, photos: O. Rylkow.

Figure 4.17. Planting (a) and cultivation (b) of *Berberis vulgaris* yearlings (c). Photos: (a), (c) O. Rylkow, (b) Iu. Mayorova.

taken into account: cultivation of planting material (seedlings of *Berberis vulgaris*); planting and cultivating *Berberis vulgaris* yearlings (within one vegetation season); beach wrack composting technology. In total, the costs per 100 plants 35 person-hours in the case of beach wrack compost application, and 11 person-hours without it.

Beach wrack monitoring costs were not taken into account in the case of growing greenery with beach wrack compost. This monitoring was carried out simultaneously as a part of the implementation of CONTRA Work Package 3 (see Chapter 4.3.2). The cost of such monitoring for beach wrack harvesting purpose only is relatively high. A cheap solution would be to use a webcam on a potentially profitable seashore. The results of Work Package 3 will allow us to choose an area suitable for that purpose on the Kaliningrad Oblast seacoast. The webcam technology was developed as part of Work Package 3 and can be recommended for further use to coordinate the beach wrack harvesting activities under the conditions of the Kaliningrad Oblast. After installing the equipment, the cost of its operation is 2 person-hours a day per month and 100 Kb of Internet traffic per month, in the case that the source of energy for the webcam is solar radiation. In general, the growing of seedlings with compost costs about 3.5 times more than without compost in the first year.

4.5.11 Conclusions

As shown by the results of the Wrack4coast experiment within the CONTRA project, beach wrack could be used for planting greenery to stabilize the dune wall. The beach wrack compost ensured nearly 2 times faster plant growth. The cost of growing plants with beach wrack compost is about 3.5 times higher than without it, while the survival rate of seedlings grown with and without beach wrack compost was practically the same after one vegetation season. At the same time, undoubtedly the viability of plants grown with compost is much higher than without it. Therefore, the precise calculations of beach wrack compost use's long-term effect can only be assessed after a few years, when the tests in winter frosts and summer droughts are passed, which is outside the project timeline. At present, the main conclusion can be made that the use of beach wrack for dune greenery is effective.

High sand content in beach wrack is not a problem when used in dunes. beach wrack contains xeno-material components, most of which are plastic.

Figure 4.18. Results of the planting of the seedlings at (a) experimental and (b) verification sites in September 2020 (one vegetation season cultivation). Photos: J. Gorbunova.

Biodegradable plastics possibly are decomposed by composting, however, this needs detailed research. Macroplastic and part of mesoplastic can be picked out during the beach wrack and compost sorting at the beginning and the end of the technological process. The most significant difficulty is microplastic, which cannot be removed by simple methods. Moreover, it can appear as a result of the crushing of macroplastic and mesoplastic. An attempt to reduce the problem is to harvest the beach wrack from a new cast.

Use of beach wrack for coastal protection greenery is close to a natural process – algae cast ashore are an essential component as a fertilizer for dune vegetation in coastal dunes formation. The thickets of vegetation at the back of the beach accumulate some beach wrack amount for effective greenery growth. However, unlike in a natural process, more beach wrack needs to make the beach wrack-based compost preliminary. Otherwise, processes of anaerobic decomposition of organic matter may occur, which would negatively affect the plants. The technology for beach wrack compost processing and its application for dune greenery were developed within the Wrack4coast CONTRA project.

The irregular appearance of beach wrack in the Kaliningrad Oblast limits its industrial use. Its collection and utilization are also a problem. A possible solution might be to use beach wrack as an additional improver in ongoing shore consolidation activities. Use of beach wrack is preferable compared to other materials, as it is not an extrinsic agent for the coastal ecosystems. Beach wrack may be involved in the soft engineering techniques that work well with nature to manage the coastline. Thus, it is possible to combine the solution of two current problems of the Baltic Sea coast in the Kaliningrad Oblast – coastal abrasion (due to dune wall consolidation) and pollution by beach wrack.

4.5.12 Alternative use, the example from the Vistula Spit (B. Chubarenko)

Another possible application of beach wrack is to use it as a filler in the first layer of wooden cells used to restore the dunes and wind-blown gaps in them. Construction of these wooden cells is a traditional way of arranging the sand accumulation before and after the foredune wall. Wood wooden constructions for sand accumulation are usable, but are not always effectively filled with sand, especially in the initial period, just after their construction (→ Fig. 4.19).

In contrast to other applications [Macreadie et al., 2017], this possible solution of using beach wrack for coastal protection purposes has not yet been tested. Beach wrack may be involved in soft engineering techniques to manage the coastline. Still, economic profit depends on the amount of available beach wrack and the possibility of collecting it from sandy shores and stony areas.

The experiment was organized at the Vistula Spit shore, where several wooden cells were constructed, and some of them were preliminarily filled with beach wrack (30 pails per each). It shows (→ Fig. 4.20) that filling the cells with beach wrack didn't influence on grass growing in the cell. The filling of the cell with beach wrack helped only at the initial stage. After several windy periods, all cells were filled with sand nearly equally irrespective of whether some of them had been partly filled with beach wrack at the beginning or not.

After the vegetation period, it became clear that beach wrack itself is not a suitable substrate for grass growing. The grass grew only in the cells, which were partly filled with ordinary hummus together with beach wrack. The grass didn't grow in the cells filled with beach wrack only.

The extent of filling the cells with sand mostly depends on the structure's configuration – a single cell doesn't work. In contrast, a two-row cell construction showed the best results, The sand was

Figure 4.19. Beach wrack could be the best initial filler for wooden cells (a) used for sand accumulation, (b) in the wind-induced blowing gaps in the foredune wall, photos: B. Chubarenko.

well stored in between two rows of cells, the second (back) row of the cell was filled, and the sand accumulated behind the back row. The cells in the front row were always filled with sand by 50-70 %.

4.6 Management, administrative and legal obstacles (B. Chubarenko)

The Kaliningrad Oblast shoreline's length is about 145 km, and only a few kilometres are managed as public beaches. These are city public beaches in Yantarny (about 1 km on the Sambia Peninsula's eastern shore) and Zelenogradsk (about 1 km on the northern shore).

Practically, only in Yantarny, there is a regular beach wrack collection experience, namely, during the every year preparation of the beach to the touristic season. The collected material is not processed; it was transported to the city landfill, stored separately without being mixed with other wastes.

In Zelenogradsk the need to collect beach wrack from the beach has emerged a couple of times only. The reason is that, due to hydrodynamic conditions and bottom sediment structure, the beach wrack is washed ashore very rarely in this area. When it happened some time ago, the city cleaning service collected the beach wrack by hand and transported it in a tractor-trailer to the local landfill, where it was stored separately from other waste. In both locations, Yantarny and Zelenogradsk some amount of the collected beach wrack was taken by gardeners from the landfill.

Collection of beach wrack is not a regular operation in the Kaliningrad Oblast. Most of the beach wrack cast to the beaches are either buried under the sand or washed back into the sea.

Preliminary analysis and discussions with experts and practitioners showed that beach wrack is not a subject of any legislative or administrative document related to Russia's environmental conservation. However, local authorities' soft measures (wooden cages for dune stabilization) could be practised within their regular coastal management responsibilities.

4.7 Conclusions and practical recommendations

Only a few kilometres of the 145 km of the Kaliningrad Oblast shoreline's length are managed as public beaches. These are city beaches in Yantarny (about 1 km on the Sambia Peninsula's eastern shore) and Zelenogradsk (about 0.5 km on the northern shore).

The regular beach wrack collection experience (the every year preparation of the beach to the touristic season) is only in Yantarny, where the collected material is not processed but transported to the city landfill, stored separately without being mixed with other wastes.

In fact, in Yantarny and Zelenogradsk, the need to collect beach wrack from the beach appeared a couple of times only. Due to hydrodynamic conditions and type of the bottom sediments, the beach wrack has washed ashore very rarely in this area.

The extensive coastal monitoring showed that the industrial use of beach wrack is limited by the spatial and temporal irregularity of its appearance on the beaches of the Kaliningrad Oblast.

A possible solution to beach wrack collection and utilization in Kaliningrad Oblast could be the use of beach wrack for compost during the activities on the greenery the coastal dunes, which is similar to a natural process. In that way, beach wrack could be involved in soft engineering techniques to manage the coastline.

The following practical recommendations were formulated:

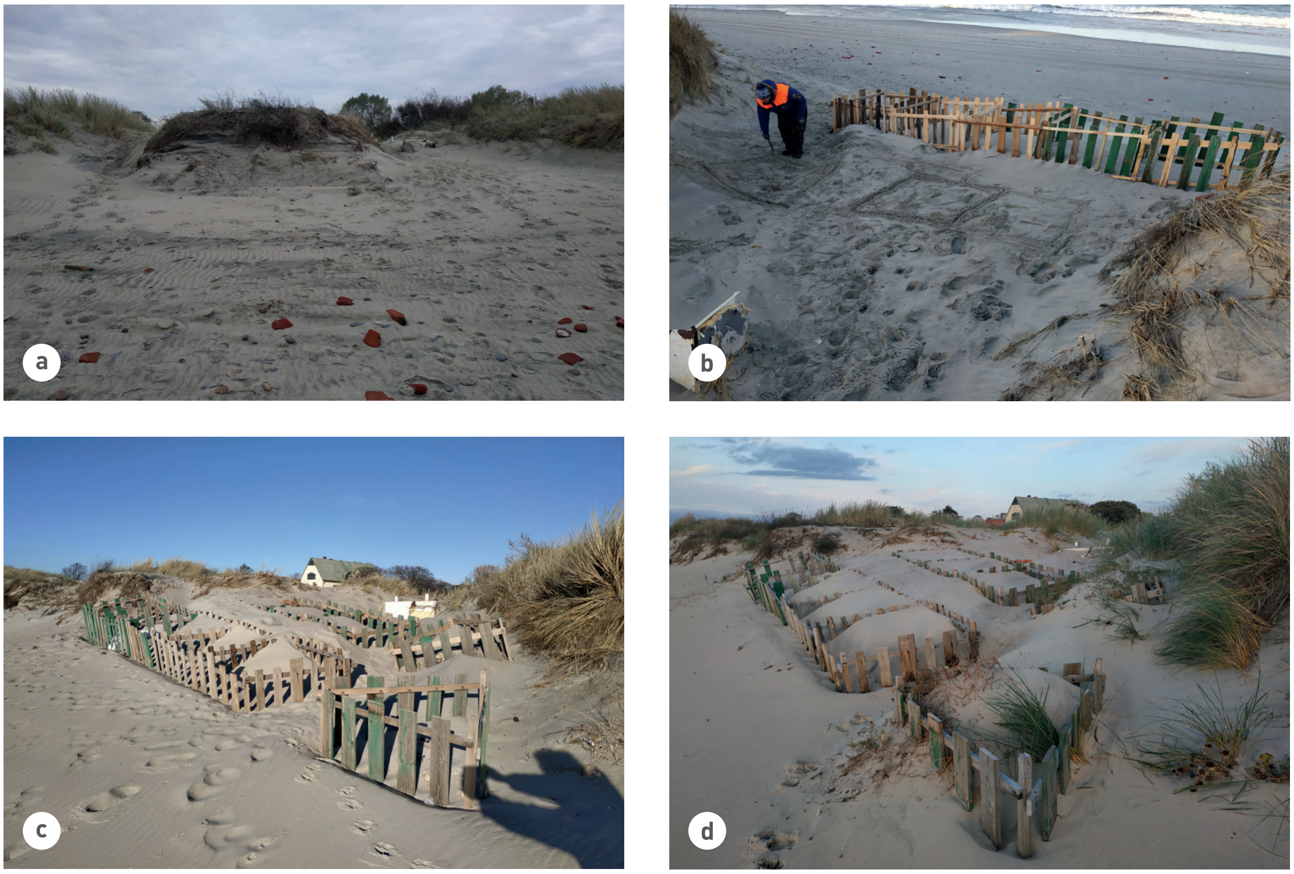


Figure 4.20. Experiment with wooden cells on the shore of the Vistula Spit: (a) the selected site (the right passage through the foredune), (b) construction process, December 2019, (c) after the wintertime, March 2020, (d) after the summer, with some grass already grown in triangular cells, which were preliminarily filled with beach wrack, October 2020. Photos: B. Chubarenko.

Beach wrack harvesting:

- Choose potentially profitable seashore areas for beach wrack harvesting, where beach wrack is cast frequently, and transport accessibility is good.
- Use webcam observations on the seashore potentially profitable for beach wrack cast to coordinate the beach wrack harvesting activities (relevant for the Kaliningrad Oblast and other areas with poor beach wrack residence time conditions).
- Attempt to harvest beach wrack from a new cast, as its flushing back into the sea usually results in the subsequent casts containing more litter.
- Beach wrack processing for dune greenery purposes:
- Before application beach wrack should be composted for 4-6 months.
- Beach wrack composting is carried out outdoors in wooden containers insulated with hay (low costs).
- The compost mass should be stirred 3 times per preparation period for aeration.

Selection of plant species for the dune greenery

- The plants have to be tolerant of a wide range of temperature, dryness, sanding, exposure of roots and recreational loads and come from the local flora species. In the experiment, Berberis vulgaris showed a good result.

Beach wrack compost application for the dune greenery:

- Yearlings with a stem length of more than 10–15 cm should be used for planting.
- The amount of compost applied should depend on the plant's needs for 1–2 years. In the case of *Berberis vulgaris* yearlings were 0.6–0.9 l of the compost per seedling.
- Compost should be applied to the roots of seedlings at a depth of 20–30 cm when planting.

Acknowledgement: The infrastructures of the Atlantic Branch of P.P.Shirshov Institute of Oceanology of Russian Academy of Sciences (supported by theme No 0128-2021-0012 of the State Assignment) and the National Park "Curonian Spit" were used.

Case study 5: The Baltic beach wrack thermal recovery and relevant analytical performances (ALREA)

Authors: Katrantsiotis Ch., Sachpazidou V., Ibrahim A., Bisters V., Burlakovs J., Hogland W.

Case study partner: Linnaeus University

Location of the case study: Kalmar, Sweden

Aim of the case study: Preliminary analysis of the possibilities to use beach wrack biomass as a feedstock for the production of soil amendment throughout thermal gasification.

Test/research done: Gasification and pyrolysis characterization during thermal conversion of beach wrack biomass at the gasification plant Renteh company (Vienibas gave 87E, Riga LV-1004).

Staff involved: William Hogland, Varvara Sachpazidou, Christos Katrantsiotis, Asim Ibrahim (all – Linnaeus University), Valdis Bisters (Renteh, Latvia), Juris Burlakovs (Geo-IT, Latvia)

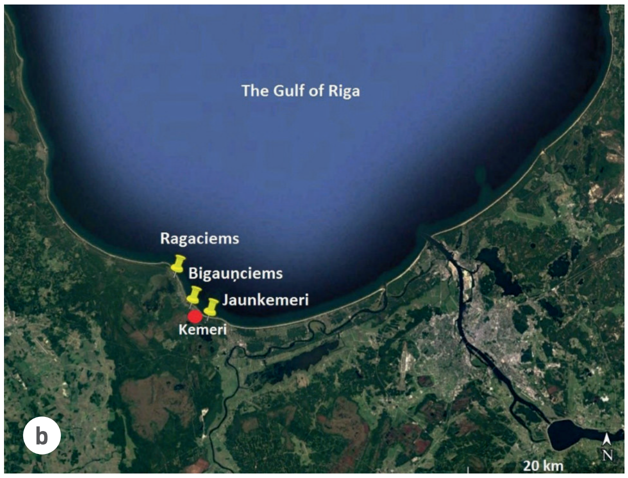
5.1 Introduction

Beach wrack is an organic material consisting of old sea-grass biomass, various other marine organisms, as well as litter that accumulate on beaches due to the action of waves, tides, and aperiodic water level fluctuations [Suursaar et al., 2014, Macreadie et al., 2017]. Despite the natural origin of this material and its significant ecological role, beach wrack becomes a social amenity and/or environmental issue, if accumulated in excessive amounts [Kirkman and Kendrick 1997, McGwynne et al. 1988, Dugan et al., 2003, Orr et al., 2005, Nordstrom et al., 2011, Macreadie et al., 2017]. Anthropogenic pressures, such as shoreline reconfiguration, eutrophication, and climate change stimulate the accumulation of wrack onshore and makes the beach wrack problems worse [Macreadie et al., 2011, 2017; Risen et al., 2017]. Moreover, marine eutrophication and climate change do not only affect the accumulation of beach wrack but also the products of its aerobic decomposition. It is estimated that the annual global carbon flux from seagrass wrack to the atmosphere ranges from 1.31 to 19.04 Tg C yr-1 [Liu et al. 2019]. Besides, the material accumulated on the seashore decomposes quickly, accompanied by a troublesome odour that keeps tourists away [Kupczyk et al., 2019]. It is therefore both an ecological problem for the eutrophicated reservoirs and the social one associated with nuisance for

Figure 5.1. Location of sampling sites in Öland (a), Latvia Bay (b) and west coast of Latvia (c) (June 2019)

inhabitants and tourists visiting seaside resorts [Kupczyk et al., 2019].

The aim is to investigate the possibilities of using beach wrack collected on the Island of Öland (Sweden) and in the Gulf of Riga (Latvia) as a feedstock for the production of soil amendment: biochar and gasification syngas as energy recovery of the waste material. This study will contribute to a circular economy and bio waste reduction through recycling /processing of the blue biomass waste. Methods of harvesting will focus on local implementation and keeping quality of the coastal sub-littoral area and beach for tourism. Efficiency analysis (+cost-effectiveness and minimum environmental impact) of choosing beach wrack as for bio covers, soil amendments or biogas will be applied including pilot tests in a reactor with different composition of mixed food waste and algae for anaerobic digestion process. Besides, proportions of beach wrack will be mixed with food residuals and household organic waste to get the most efficient biogas production. The business model will also include the use of algae in agriculture for local farmers and non-governmental organizations (NGOs) and energy sectors (targeted at biogas company).



5.2 Location and geographical description

Samples of beach wrack were collected from sandy beaches of Stenåsa, South-Eastern Öland and Vikegård: North-Eastern Öland, in June 2019 (→ Fig. 5.1a). Öland is a c. 140 km long island in the southern Baltic Sea, near mainland Sweden. The samples were analyzed for calorific values as well as ultimate and approximate composition analysis.

On the South Baltic coast, wrack material was collected from sandy beaches in the Gulf of Riga (Jaunkemeri, Bigauņciems, Ragaciems) and the West coast of Latvia (Liepaja) (→ Fig. 5.1 b,c). The Gulf of Riga has a surface area of 17 913 km^2, a volume of 406 km^3, a maximum depth of 52 m, and an average depth of 23 m [Suursaar et al., 2014]. The largest sample for gasification tests was collected at the Jaunkemeri beach. Termogravitometry and ultimate analysis was made for the collected beach wrack. For anaerobic digestion, three seaweed types were collected in Kemeri (Gulf of Riga): brown, red, and green algae.

5.3 Description of beach wrack effect as a natural process, local peculiarities and characteristics

Beach wrack offers many ecosystem services and a link between the marine and terrestrial environments. It provides habitat (food, nesting, and shelter) to important animal communities including invertebrates and shorebirds that inhabit shorelines and contributes to the coastal and marine food web systems though supplying essential nutrients, as the organic material decomposes and breaks down [Kirkman and Kendrick, 1997, Dugan et al., 2003, Orr et al., 2005, Nordstrom et al., 2011]. Beach wrack supports microbes and other smaller organisms utilised by plants and fish including important commercial fishery species [Kupczyk et al., 2019]. Beach-cast seagrass accumulations are typically long-lived, taking as many as 3–5 years to fully decompose into detrital matter attributed to their cellulose refibre with characteristics that inhibit the breakdown of the vegetative matter [El-Gamal and El-Kader, 2019]. Thus, beach wrack contributes to the protection of the shoreline and the coastal dunes by providing a physical barrier that dissipates the wave energy, reducing their impact force on the shore [Macreadie et al., 2017, Kupczyk et al., 2019]. Furthermore, beach-cast seagrass wrack enhances the formation and stabilization of coastal dunes and beaches, due to the fibrous composition of seagrass, acting as a trap that binds drifting sands and reduces the erosional process in winter [PIRSA 2014, Kupczyk et al., 2019].

The process of detachment, transport, and accumulation of beach wrack depends on a variety of hydrodynamics and topographical factors [Suursaar et al., 2014]. The material may originate from the nearby areas but can also be carried as algal mats from distant locations, as winds and currents can move the masses towards the shore accumulating huge drift walls [Vahteri et al., 2000]. The beach morphology also determines the morphology of wrack depositions, with the latter being rather patchy in a curved or indented coastline [Orr et al., 2005]. Buoyancy characteristics of the wrack are another factor, as different macrophyte species can be cast ashore more easily than others [Suursaar et al., 2014]. Throughout a year, beach wrack decays and becomes detritus with some species decomposing faster than others. Dry-wrack particles on the shore can become more buoyant and can be moved back to sea during high water events [Suursaar et al., 2014].

The distribution of species as well as the total biomass of the communities has a strong regional pattern related to different ecological conditions [Martin, 1999]. In the Baltic Sea, more than 500 species of macroalgae, aquatic vascular plants, charophytes, and bryophytes have been recorded [HELCOM, 2012, Suursaar et al., 2014]. The number of marine species decreases with the salinity gradient, and the Gulf of Riga has one of the lowest macro vegetation diversity. Forty-three species of macroalgae have been identified in this area [Martin, 1999]. Fucus vesiculosus L. is one of the most common Brown algae in the Gulf of Riga and on the rocky bottoms of the Baltic Sea coastal areas where it forms dense colonies [Torn et al., 2006, Balina et al., 2016]. Other frequent species in the Gulf of Riga are filamentous algae such as Ceramium tenuicorne (Kützing) Waern, Polysiphonia fucoides (Hudson) Greville, Pilayella littoralis (Linnaeus) Kjellman as well as Battersia Arctica (Harvey) Draisma, Prud'homme & H. Kawai [Martin 1999, Suursaar et al., 2014]. In Southern Sweden and Öland, the most common species are Polysiphonia fucoides (Huds.) Grev., and Furcellaria lumbricalis (Huds.) Lamou, as well as sparse Fucus vesiculosus L. and Fucus serratus L. stands (Malm, unpubl.) [Malm et al., 2004].

5.4 Why beach wrack is a problem?

The brackish-water Gulf of Riga is considered one of the most eutrophic basins in the Baltic Sea [Suursaar et al., 2014]. One apparent consequence of eutrophication is an increased production of drifting, filamentous algae, dominated by a few out of several co-occurring opportunistic species [Malm et al., 2004 and references therein]. The nutrients released from decomposing beach wracks can further exacerbate the eutrophication problem (Lastra et al., 2008). The decomposition of beach wrack is often perceived as a kind of "pollution", which promotes insects and bacteria causing a troublesome odour and thus reducing the tourist attractiveness of the seaside resorts and the recreational value of beaches [Kupczyk et al., 2019]. Its removal can therefore be an important management task. Noticeable is that the amount of washed-out algae is not monitored in Latvia [Balina et al., 2017].

The conversion of beach-wrack to biochar could be a viable environmental solution that can provide a value-driven model to sequester and recycle nutrients [Ross et al., 2008; Bird et al., 2011]. Previous studies have shown that "microalgae biochar can provide direct nutrient benefits to soils and stimulate crop productivity and will be useful for the application on acidic soils" [Bird et al., 2011]. Biochar has the potential for an even greater impact on climate through its enhancement of the infertile soil productivity and its effects on soil GHG fluxes than bioenergy, in which CO_2 fixed in the biomass by photosynthesis is returned to the atmosphere quickly as fossil carbon emissions are offset [Woolf et al., 2010].

5.5 Technology tested (Methods and Results)

5.5.1 Beach wrack analysis

The calorific value of the sample from Stenåsa was analysed by incineration in a bomb calorific meter, according to the standard method LVS EN ISO

18125:2017. The ultimate analysis was made according to the methods: LVS EN ISO 16994:2016 (for Cl, S) and ISO 16948:2015 (for C, H, N), the content of O2 was calculated. Proximate composition was estimated using the express method described by Agrawal (1988), the same results are used as thermogravimetry (TG) data (see 5.5.6). For the content of metals and phosphorous, around 250 mg of samples were transferred to Teflon capsules, 9 mL of concentrated HNO3 and 1 mL of 30 % H2O2 were applied to each sample, the capsules were sealed and samples were digested in a microwave oven (Milestone Ethos Easy) at 200 ˚C and 49 bar pressure for 15 minutes. Metal concentrations were analyzed using ICP-OES (Thermo Scientific iCAP 7000 series).

5.5.2 Gasification tests

Gasification is a chemical process that converts carbonaceous material such as biomass and coal into gaseous fuel or chemical feedstock. This gaseous fuel is known as producer gas or syngas which contains CO_2, H_2, CO, H_2O, CH_4 and N_2 compounds. Air gasification has been applied in the beach wrack gasification process. Surplus char which is formed from the pyrolysis process is heated by supplying a limited amount of air in the gasifier. The temperature of the reactor is reliable on the feedstock feed rate and airflow rate. Higher tar and lower gas are produced by supplying low inlet air. Lower heating gas (3–7 MJ/Nm^3) is produced which is appropriate syngas applications either for power production or heat recovery in boilers. Drying, pyrolysis, gasification, and oxidation are the four main zones in the gasifier depending upon the relative movement of the gasifying agent and feedstock. Different temperatures and different reactions occurred in different zones. Each zone is relying upon feedstock, gasifying agent, temperature, particle size, moisture content, and chemical composition.

Drying Zone

It receives energy from the other zones through heat transfer to reduce moisture content by up to 5 %. The drying process occurred at 100°C -150°C. A chemical reaction is not taking place in this zone.

Pyrolysis Zone

It is known as the DE volatilization zone, and the process occurred in this zone at 150°C-700°C. DE volatilization of feedstock is occurred due to the heat transfer from a reduction zone. Higher temperature difference occurred due to hot gases and cold feedstock. The thermal and physical properties of biomass feedstock are changed due to the higher temperature. Gases, liquid (oil and tars), and char are the products of this zone.

Oxidation Zone

It is known as the combustion zone. In this zone, feedstock carbon is burned through oxygen. Temperature ranges from 700°C to 1,500°C which is the highest among all zone and exothermic reactions occur in this zone. Air, which is a gasifying agent, is entered in this zone into the biomass feedstock bed. Carbon dioxide proportion is increased, and the oxygen percentage is decreased while using air as a gasifying medium. Following chemical reactions take place:

$C+O_2 \rightarrow CO_2$ -401.9 kJ/mol

$H+1/2O2 \rightarrow H_2O$-241.1 kJ/mol

Gasification Zone

It is known as the reduction zone. Temperature ranges from 800°C to 1,100°C. The reaction is mostly endothermic as follows:

Reaction 1: $C+H_2O \rightarrow CO+H_2$ (+131 kJ/mol)

Reaction 2: $C+CO_2 \rightarrow 2CO$ (+172 kJ/mol)

Reaction 3: $CO+H_2O \rightarrow CO_2+H_2$ (-41.2 kJ/mol)

Reaction 4: $C+2H_2 \rightarrow CH_4$ (-74.8 kJ)

Torrefaction, also known as destructive drying and slow pyrolysis, is a mild pyrolytic process that recently received wide attention of the scientific community as both: the method of the pre-treatment and upgrade of low-quality fuels [Chew and Doshi 2011, Chen et al. 2015, Białowiec et al., 2017], as well as for the production of soil amendment, called biochar [Hekkinen 2019]. This process may be organised at scales ranging from large industrial facilities down to the individual farm [Lehman and Joseph 2009], and even at the domestic level [Whitman & Lehmann 2009], making it applicable to a variety of socioeconomic situations. The study of Macreadie et al., 2017 provided clear evidence that the conversion of beach-wrack to biochar could be a viable environmental solution for dealing with unwanted wrack, offsetting carbon emissions, and providing commercially valuable products. The use of macroalgal biomass for biochar (charcoal) production, with energy co-generation potential, provides a value-driven model to sequester C and recycle nutrients [Ross et al., 2008; Bird et al., 2011]. Biochar has demonstrated applications as a soil ameliorant capable of improving water holding capacity, nutrient status, and microbial ecology of many soils

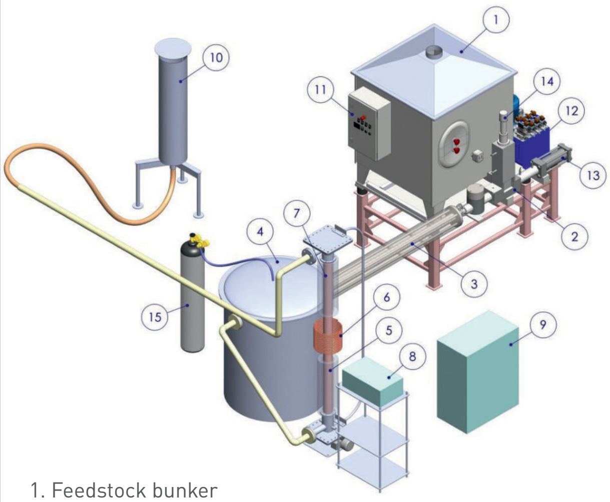
[Lehmann et al., 2006; Lehmann & Joseph, 2009; Thies & Rillig, 2009]. Results of [Bird et al., 2011] showed that macroalgal biochar has properties that provide direct nutrient benefits to soils and stimulate crop productivity and will be especially useful for the application on acidic soils. [Bird et al., 2011]. In contrast to bioenergy, in which all CO_2 that is fixed in the biomass by photosynthesis is returned to the atmosphere quickly as fossil carbon emissions are offset, biochar has the potential for an even greater impact on climate through its enhancement of the productivity of infertile soils and its effects on soil GHG fluxes [Woolf et al., 2010].

5.5.3 Choice of gasification tests

The choice of the gasification technology was driven by the specific nature of the beach wrack as received. The gasification of carbonaceous solid fuels is a well-known and well-researched process. There are several types of gasifiers: downdraft, updraft, fluidized bed and others. The choice of gasifier technology is largely determined by the nature of the fuel used.
Beach waste is characterized by a very high content of inert substances. Sand and rocks can be a significant part of the mass, depending on the type of waste collection. Of particular relevance to this factor is the mechanized collection method. Also, the bulk density and thermal conductivity of such waste are very low. Limiting the small particle flying process is a major challenge for conventional gasifiers. The thermal conductivity of the fuel is very important in the initial phase of the gasification process, pyrolysis. All of this imposes huge restrictions on the choice of gasification technology.
Another factor in the choice of gasification technology is the requirements for the synthesis of gas composition and tar content. This factor significantly limits the use of synthesis gas. Dirty and tar-rich synthesis gas can only be used as fuel for combustion in boilers. High purity gas can be used as fuel for power and heat generation in internal combustion engine power plants. High purity synthesis gas can be used as a feedstock for chemicals and second-generation biofuels.
The technology with potentially very high gas purity has been selected for beach wrack gasification tests. This utilizes a hydraulic briquetting press system built into the gasifier to increase fuel density and thermal conductivity, which simultaneously performs functions of a fuel compactor, gas leak shutter and dispenser. In the process, the amount of flying fuel particles are minimized. The installation is very compact and transportable. Additionally, the resulting pyrolysis/gasification char is obtained in the form of solid briquettes, which can extend the applicability and improve the logistics of the product.

5.5.4 Description of the beach wrack gasification test facility

Thermal gasification tests have been carried out to determine the useful use of offshore waste. Before the gasification tests, the waste samples were cleaned of bulky inert impurities and the samples were dried from the initial 80 % moisture to 20 % moisture content by weight of the wet substance Drying was done by spreading algae waste on a metal fine grid in a 100-150 mm layer and blowing air through this layer at a temperature of 30-40 C. The average drying time was 72 hours. After the drying process, the beach wrack feedstock was packed in airtight polyethene bags and prepared for gasification tests.
Wrack gasification tests were made on an innovative gasification plant for pyrolysis of various wastes and the thermal cracking of pyrolysis gas products (→ Fig. 5.2. The apparatus consists of an extruder-type pyrolizer/gasifier, a pyrolysis product separation chamber, a thermal cracker for gaseous pyrolysis products and a gas burning torch. The gasification process does not use air or oxygen as a gasification agent. The plant has an allothermal gasification process using an external heat source. Nitrogen is the gas that commonly used for inserting in the plant and enhanced process safety. The machine is in continuous operation mode.
In the extruder-type pyrolizer (3), the fuel is compacted in a continuous 42 mm diameter briquette blast, pressed into a heated extruder utilizing a hydraulic piston. The operating temperature of the extruder was set and automatically adjusted to 300-600 °C. The primary reforming of the fuel into pyrolysis gas and coal is carried out in the extruder.
In the pyrolysis product separation chamber (4), the pyrolysis gas is separated from the coal. The carbon is stored in an airtight container. After cooling, the coal is unloaded from the container and sent to a laboratory for analysis. The pyrolysis gas is fed to a secondary high-temperature reformer (6) where the pyrolysis gas is heated to 800–1,200 °C. At elevated temperature, high turbulence thermal tar cracking takes place and the heavy organic gaseous substances are reformed into the synthesis gas components H_2, CO, CO_2. At the output of the secondary reformer, the gas is cooled and the heat



1. Feedstock bunker
2. Hydraulic press feeder
3. Heated extruder
4. Gas and char accumulation tank
5. Secondary gas cracking
6. External inductive heater
7. Gas cooler
8. Inductive heater resonator
9. Inductive heater power box
10. Flare
11. Control cabinet
12. Hydro station
13. Hydrocilinder
14. Prior hydropresser box
15. Nitrogen balloon

Figure 5.2 Experimental gasification plant

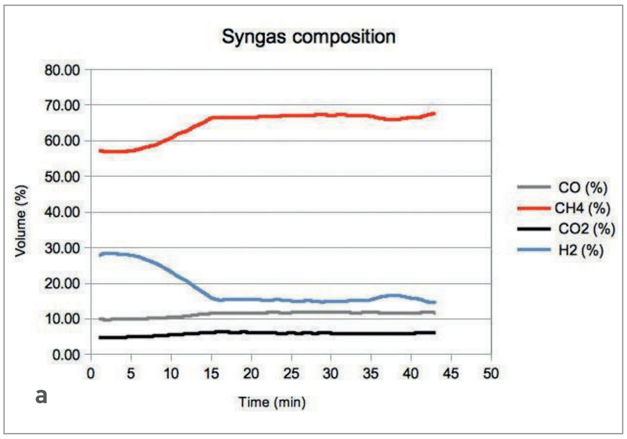
consumed in the process is recovered. The resulting synthesis gas samples are analyzed on-site with a portable gas analyzer, and the gas samples are collected in sampling bags for further analysis in the laboratory. The synthesis gas, which is produced by the gasification process is burnt in a torch (10) located outside the space.

5.5.5 Anaerobic digestion tests

Biogas as gaseous energy is derived from organic matter (biomass) by anaerobic digestion or fermentation. Methanisation is an ancient, naturally occurring process where bacteria association disintegrates organic matter. In this study, for anaerobic digestion tests, three types of seaweed were collected at the Gulf of Riga Kemeri seaside: brown, red and green algae. Seaweed has been collected as beach wrack from the embankment piles of washed-up feedstock and had an extensive admixture of sand as well as unpleasant smells. As the first step, organic dry matter content was determined. For instance, red algae had the lowest dry matter, just 3.04 %. Therefore, a simple technique for washing the macroalgae was performed and sand separated as much as possible. However, a lot of sand was embedded in the algal pulp and was not fully separated.

These algae samples were tested regarding the chemical composition of standardized methodologies ISO 6496:1999. For each sample and starter (yeast) dry matter, organic solids and ash content were determined. The analysis was made by standard methods. Full dry matter was determined using equipment Shimazu at 120oC temperature, organic matter composition by drying oven Nabertherm assistance at 550oC. Each group of raw materials was carefully weighed by weighing the starter and thoroughly stirred. All samples were used with the same yeast-digestate from the digester. All algae before analysis and filling in the bioreactors were chopped into 3cm pieces. The 0.75 l bioreactors were charged with 20 g of raw materials and 500 g starter (the weight recorded to 0.2 g accuracy). All data were recorded in the journal of experiments and computer. Bioreactors R2 - R4 was charged with 20 g greasy Brown algae, bioreactors R5 - R7 was charged with a 20 g 24 h tap water held Brown algae, bioreactors R8 - R11 – with around 20 g per hour and the bioreactors R12 - R15 through 20 g greasy and dried Brown algae. Digestate was also weighed, and its dry matter, ash, and organic dry matter content were determined. Measurement accuracy was ± 0:02 pH, ± 0.025 l gas volume and ± 0.1 °C temperature. The produced biogas periodically was measured and CH_4, CO_2, O_2 and H_2S composition were determined. Starter/yeast was taken from an active biogas fermentation bioreactor. Biogas production amount was investigated using laboratory equipment consisting of 16 x 0.75-litre bioreactors. For digesters, standard vessels were used. The oven fan provided continuous operating temperature. The gas composition was measured with a gas analyzer GA 2000. Methane, oxygen, carbon dioxide, and hydrogen sulfide content of the biogas was measured, as well as pressure and recalculation to normal gas volume was done. Weighing scales were used (Kern FKB 16K02) and pH measurement was made with pH meter with stationary accessories (PP-50).

In the second study, the Brown algae from Riga Bay seashore were studied separately by applying a variety of pretreatment methods to test actual biogas/methane yield of pretreated algae material. The tests were carried out by similar methods as in the first study to provide a comparison of the testing



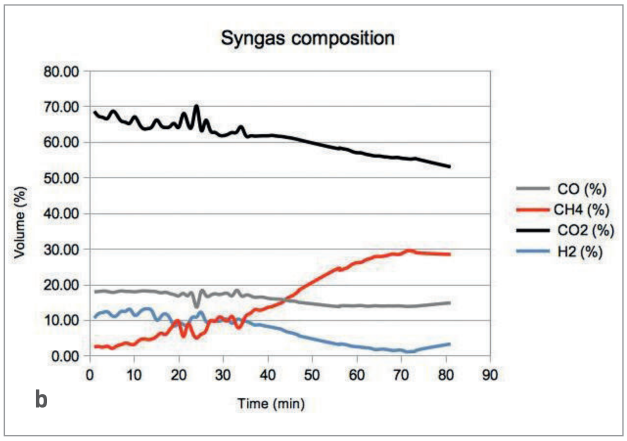


Figure 5.3. Synthesis gas composition in experiment no. 1 (a): stabilization of the gasifier operation occurs within 15 minutes, the inert nitrogen content of the system is not included; and no. 2 (b): no gasifier stabilization, no system inert nitrogen present.

conditions. For freshly collected Brown algae three types of pre-treatment were tested. In the first test, the Brown algae were kept in the water container for 24 hours to reduce salt concentration in the samples. In the second pretreatment option, the Brown algae were rinsed in a stream of water for one hour enabling better separation of sand particles and enhancing the dissolution of the salts with the interaction of larger volumes of freshwater. In the third method, the Brown algae were only dried and the dry part of the sand was separated but still, sand presence remaining. The resulting methane quantities were further compared with the ones, which were obtained from the raw Brown algae without any pretreatment.

5.5.6 Results from beach wrack analysis

Heating (calorific) values of the analysed sample from Stenåsa should be considered as low and the studied substance is not applicable as a fuel (HHV 8.96 MJ/Kg and LHV 7.55 MJ/kg). The proximate composition is characterised by relatively low content of volatile matter (20.4 %), significant content of fixed carbon (11.8 %) and very high content of ash (33.9 %). The ultimate analysis shows a relatively low proportion of carbon (21.1 %) and hydrogen (2.4 %) and high proportions of oxygen (40 %) and mineral compounds. Contents of sulphur and chlorine (0.7 and 0.2 %) should be considered as acceptable for thermal treatment. Analyses of the composition of mineral part show that samples are mainly characterised by a high content of phosphorous, potassium, and nitrogen that makes them perspective for the use in fertiliser production. No problematic concentrations of heavy metals were found.

Thermogravimetric analysis shows that the first decomposition maximum may be observed at >130 °C which should be interpreted as the evaporation of bonded water. The volatilisation of light organic compounds is possible during this stage, while it is impossible to analyse this fact by using only thermogravimetry. Additional measurements are needed for the research of this question. The second maximum takes place at 200-500 °C, which must be interpreted as the pyrolysis of carbohydrates. The content of fixed carbon (>10 %) should be considered as high enough for the production of biochar. Around 50 % of total carbon in feedstock may be retained as fixed char under standard circumstances. FTIR spectroscopy results show the significant share of carbohydrates and carboxylic acids as well as the presence of unsaturated hydrocarbons and amine salts. Our results are consistent with those from [Roberts et al. 2015] who pointed that "Algal biochar is comparatively low in C content, surface area and cation exchange capacity CEC), but high in pH, ash, N and extractable inorganic nutrients including P, K, Ca and Mg". A blending of seaweed and lignocellulosic biochar could provide a soil ameliorant that combines a high fixed C content with a mineral-rich substrate to enhance crop productivity" [Roberts et al., 2015].

5.5.7 Results from marine gasification tests

Gasification tests were performed on the material from Latvia. The tests were conducted with a limited amount of fuel. This limited the duration and number of tests. Of the 1,300 kg collected in marine waste, 219 kg of fuel was obtained after drying. Six gasification experiments were performed, of which 2 were representatively used for detailed analysis (→ Fig. 5.3 and 5.4). Some of the intermediate runs were needed for calibration of the feeding and gas formation ratio to reach close to steady-state

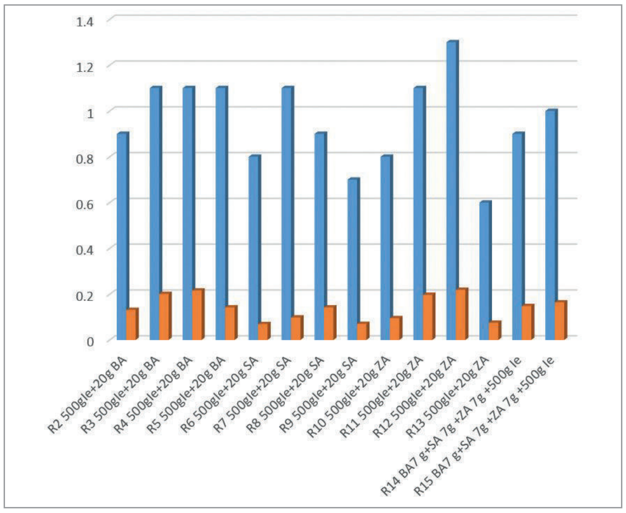


Figure 5.5 Biogas (blue column) and methane (orange column) yields in liters from each bioreactor (x axis). Y axis represents Gasol L.

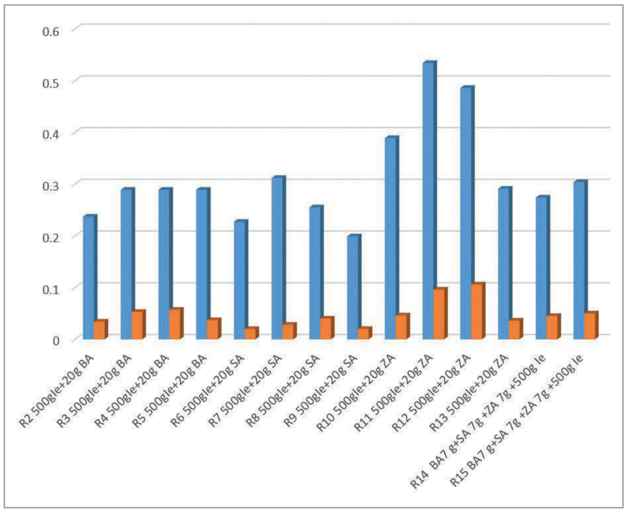


Figure 5.6 Biogas (blue column) and methane (orange column) yields from the various pretreatment of Brown algae-X axis represents the bioreactors and the Y-axis represents the specific gases yield L·g-1dom

of the pyrolysis/gasification process. As a result of the tests, the experience was gained in conducting larger scale beach wrack gasification experiments and in improving the design of the gasifier to work with this fuel further. Both gasification experiments were done under substantially different conditions at different mechanical pressure settings of the pyrolysis zone. The results confirm the initial assumptions and previous experience with this type of gasification plant.

5.5.8 Results from anaerobic digestion tests

The methane from all algae (green, brown and red) collected from the Kameri seaside at the Gulf of Riga represents a very small part of the biogas volume (→ Fig. 5.5). From a carbon perspective, more carbon dioxide was absorbed from the beach wrack composition that was originated at the Gulf of Riga. This shows that the biomass hydrolysis took place, but methanogenesis was weak. Therefore, the raw materials were methane forming bacteria inhibitors. It was dissolved salts in the seawater mixture. The actual salt concentration analysis was not undertaken, as it falls out of the scope of the current biogas/methane yield tests.

Most biogas and methane are obtained from the digesters with dried Brown algae. The results between the washed and unwashed Brown algae are considerably different. Biogas and methane yield was on average higher out of the water stream and Brown algae passively kept in the water for 24 hours. This can be attributed to the ignition effect of the seawater. Anaerobic fermentation microorganisms are influenced to slow down bacteria activity for the fermentation process. Biogas and methane yields from the various pretreatment of Brown algae show that the lowest yield is demonstrated by bioreactor with dried feedstock (→ Fig. 5.6). The largest yield is demonstrated by samples washed in a stream except for reactor R9. We assume it is related to some deviation of the washed-out salts in the particular sample and can be attributed to a mechanical problem. There is a considerable difference between washed and unwashed samples, so it gives a clear recommendation for pretreatment necessity for better yield results even in anaerobic digestion.

Methane content is shown in Figure 5.7. The relatively low methane content in the biogas on average is explained by the fact that the raw materials still possess sea salts, which still inhabit the methane-forming bacteria. The fact that relatively better methane content of biogas digesters demonstrated from dried samples does not support the relationship of less yield with the higher presence of salts (which is the case with dried/unwashed material). However, it should be noted that in these samples dry organic matter content was more than twice compared with others, therefore bacteria in yeast most likely entered into the digestion process before inhibition started to interfere with the methanation.

5.6 Management-related obstacles

Given the ecological functions of beach wrack, the implementation of recreational beach wrack management strategies that work with rather than against nature is a necessary step towards more sustainable use of beaches. According to Vieira et al., 2016 "Wrack removal may cause ecological problems by disrupting pathways of decomposition and nutrient exchange between marine and terrestrial ecosystems, which is the basis for primary production and food chains of nearshore waters". It may also alter the physical characteristics of the beach, causing changes in the composition of supralittoral invertebrates, higher erosion of the beach profile, and loss of the frontal dune [Vieira et al., 2016]. One mitigation strategy might be to educate beach users to understand the ecological value of wrack to coastal wildlife, and that this organic material needs to be left on some sections of beaches. The local factors should also be considered in human disturbance assessments: (a) beach type; (b) wrack debris features and (c) specific density and composition of individual species associated with wrack [Vieira et al., 2016]. To achieve this, ecologists and coastal recreational managers should work and plan together sustainable management strategies that do not inflict generating environmental and economic losses [Vieira et al., 2016].

5.7 Administrative and legal obstacles

Throughout this project, it was found from local authorities that beach owners, municipalities, or cleaning companies conduct the cleaning of beach wrack deposits every year on some selected beaches. This process is called "beach grooming" and is common practice in other regions of the Baltic Sea, where considerable amounts of beach wrack are accumulated, particularly on the sandy beaches and less frequently on the rocky shorelines. The beach wrack removal differs from the beach to beach and also among Baltic countries, as the accumulation on beaches varies between coastal sections and the existing management standards. In Sandy beaches, the removal operation is made by grid bucket method that is a tractor with a fork in the form of a rake (grid bucket) and usually placed in a pile-up on the beach. Most local authorities carry out the beach wrack removal operations mainly during the summer season. After the touristic period, the beach wrack piles up on the beach are pushed back in the water. In the Baltic Sea, there are various traditional uses of the accumulated beach wrack. For instance, it is used by the farmers to make compost, fertilizer, and fuel for recovering green areas and livestock. Besides, beach wrack has been used as packing and construction material. Apart from the agriculture applications,

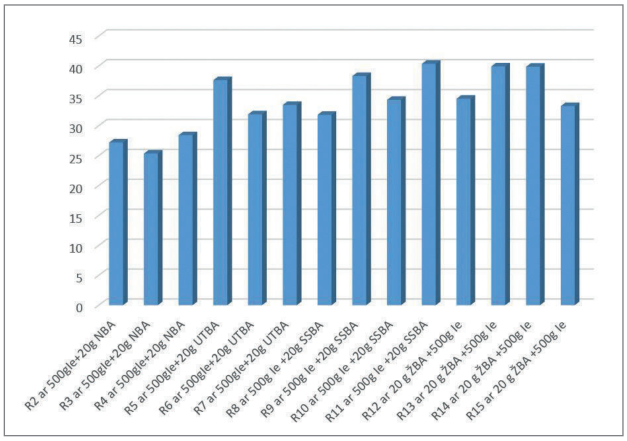


Figure 5.7 Methane content % on average of the different pre-treated samples in different bioreactors

beach wrack is used for making insulation materials (roofs, interior walls and basement ceilings).

5.8 Potential solutions associated with the ecological dimension, targeting network-based, local and transregional opportunities

The collection and management of beach wrack pose a financial burden and a range of challenges for local communities, municipalities, and interested stakeholders and are also often in direct conflict with measures to safeguard the environment. Some of the challenges are the significant cost effect for beach cleaning, the organizational challenge for the municipalities to clean, transport and store the "organic waste". To address this conflict and to balance opposing interests, CONTRA conducts a fair and comprehensive evaluation of all environmental, social, and economic aspects of beach wrack management. This evaluation includes ecological impacts of beach wrack collection, industrial cycles of beach wrack processing, and value chains of beach wrack-based products or services. Potential products and services include fertilizer, soil improvers, biochar, biocover, coastal protection, biogas production, and water quality improvement.

Based on the experience from the gasification tests, it can be concluded that beach wrack as thermal treatment feedstock is suitable for use for gasification. When analyzing the potential application of gasification technology for the treatment of the beach wrack, it is essential to take into account the fact that under real conditions the process can be energy-intensive due to the need for beach wrack drying. However, through designing an efficient recovery of the heat it is possible to redirect a major part of the heat for low-temperature drying, therefore, improving the overall energy balance of the treatment process. Moreover, the high content of inert substances in the fuel is not an obstacle to the use of tested technology. If drying is applied as low energy input the gasification of the beach wrack is a very suitable method due to flexibility in coping with high ash contents (high concentrations of sand particularly in beach collected feedstock) as well as the economical and logistical arguments that may gain higher importance in the choice of upscale methods. The high level of methane has been quite specific and unique in the course of the tests. It may be attributed to a specific pressure and indirect heating conditions which deserve further analysis by applying repetitive test runs with a larger amount of the feedstock to gain a more continuous process. It may have far-reaching new opportunities for small scale distributed beach wrack utilization systems in this region.

It is recommended to continue research on widening the gasification method to integrated drying systems and improved energy recovery to elaborate on practical upscale solutions. Additional comparison on biogas production out of the beach wrack can be made in the process of anaerobic digestion, which is an alternative approach when higher moisture content feedstock is used combined with other wet waste processing like water treatment sewage sludge.

For anaerobic digestion, the results show that for better yields rinsing of seaweed before feeding into anaerobic digestion is preferable. In cases where it is not possible to do biogas/methane yields will be negligible and recovery of the waste into biogas will not be economically feasible. With or without pretreatment seaweed biomass can be used in the co-fermentation of other waste streams like sewage sludge or manure. Such co-fermentation will optimize the C: N ratio and will neutralize the inhibiting effect. For clarification of the optimal process parameters, further studies and tests are recommended.

5.9 Conclusions

The study includes the performance of gasification technologies on wrack material for carbon-based feedstock thermal recovery and testing out biogas potential from algae using anaerobic digestion equipment. The analysis is based on beach wrack from Öland, Southern Sweden and Latvia. The results from gasification tests performed on material from Latvia suggest that the studied samples are suitable for the use as a feedstock for the production of biochar and gasification application for the regeneration of the beach wrack material. The quality of the char and synthesis gas produced is consistent with the original concept of gasification biomass although beach wrack, in general, has much higher ash content than other biomass waste feedstocks, and the presence of a high concentration of inorganics require proper gasification process conditions. For the anaerobic digestion, the results show that from the coast washed beach wrack, a small amount of methane can be generated per dry organic matter if there is no pretreatment and conditioning of the samples undertaken. The results confirm that washing of Brown algae as pretreatment for anaerobic fermentation avoid salts inhibition and thus can make good use of biomethane production. With the pretreatment of Brown algae in running water, the feedstock is well suited for good volume biogas generation for energy recovery and use in other applications of bio SNG.

Our goal in this study is to develop a practical framework for obtaining a uniform sample recommendation on thermal recovery and relevant analytical performances that are targeting administrative, political and regional communities. To improve future research and promoting innovative and sustainable knowledge among society, we make the following suggestions from our study design:

- The results from gasification tests performed on material from Latvia suggest that studied samples are suitable for the use as a feedstock for the production of biochar and gasification application for the regeneration of the beach wrack material.
- The quality of the char and synthesis gas produced is consistent with the original concept of gasification biomass. Although beach wrack, in general, has much higher ash content than other biomass waste feedstock and the presence of a high concentration of inorganic materials, requires proper gasification process conditions.
- For the anaerobic digestion, the results show that from the coast washed beach wrack, a small volume of methane is generated per dry organic matter if there is no pretreatment and conditioning of the samples undertaken.
- The results confirm that washing of Brown algae as pretreatment for anaerobic fermentation avoids salts inhibition and thus can make good use of biomethane production.
- Beach wrack may be employed on reclaimed land when mixing with straw from cattle boxes

and liquid manure for growing of feed corn on the new land for agriculture. It probably increases the decomposition of the soil remaining humus from the pine tree forest. Ordinary composting is also possible if pollutant concentration is not too high.

- There is a possibility of bio-coal that can be produced from beach wrack that would be mixed with sediments to provide stabilization of road-deposited sediment pollutants.
- The introduction of beach wrack as an energy resource rather than waste can stimulate market implementation.
- Of major importance is to simplify administrative procedures for beach wrack management and continue its energy development.
- Raising the awareness of the flexibility and new applications that drive gasification and anaerobic digestion technologies to gain greater prominence.
- Thermal energy recovery and relevant analytical performances can be considered as energy efficiency approaches for a tremendous variety of products among them beach wrack biomass.
- Globally there is a strong strategic desire to use regional indigenous energy resources to produce the energy and products needed for regional economic growth. Beach wrack is one of the regional indigenous energy resources for Baltic countries.
- Gasification facilities are diverse in the development of safe designs and safe operations to address multiple energy security concerns.
- Gasification and anaerobic digestion technologies can meet market needs throughout the world and contribute to zero waste management.
- Innovative work is underway on thermal recovery and relevant analytical performances towards circular economy solutions for the management of beach wrack residues to bioenergy via gasification and anaerobic digestion.
- It is interesting to quantify the total amount of beaches in the Baltic Sea region, including the managed, unmanaged and tiny beaches. As there is a need to model and monitor the aquatic environment.

5.10 Strategic principles of ALREA and practical recommendations, which target administrative people and politicians

The introduction of beach wrack biomass as a source of energy can stimulate market implementation.

The major importance is to simplify administrative procedures for beach wrack management and continue its energy development.

Raising the awareness of the flexibility and new applications that drive gasification and anaerobic digestion technologies to gain greater prominence.

Gasification and anaerobic digestion waste-to-energy processes can yield a tremendous variety of products among them beach wrack biomass.

Globally there is a strong strategic desire to use regional indigenous energy resources to produce the energy and products needed for regional economic growth. Beach wrack is one of the regional indigenous energy resources for Baltic countries.

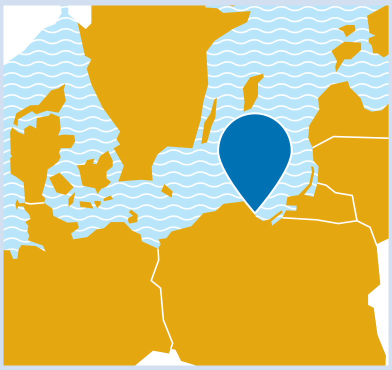
Gasification facilities are diverse in the development of safe designs and safe operations to address multiple energy security concerns.

Gasification and anaerobic digestion technologies can meet market needs throughout the world and contribute to zero waste management.

Innovative work is underway on gasification technologies towards circular economy solutions for the management of beach wrack residues to bioenergy via gasification and anaerobic digestion.

It is interesting to quantify the total amount of beaches in the Baltic Sea region, including the managed, unmanaged and tiny beaches. As there is a need to model and monitor the aquatic environment.

Case study 6a: Nutrient and pollutant flux to coastal zone originating from decaying algae & plants on beaches (WAIT)
Case study 6b: Beach wrack treatment in reed bed systems (FERTIWRACK)



Case study partner – WAIT: Institute of Oceanology of Polish Academy of Sciences

Location of the case study: Puck Bay, Poland

Aim of the case study: To evaluate beach wrack associated transport of substances from sea to beach, and identify beachcast removal impact on the ecosystem.

Test/research done: Analysis of beachcast and sand chemicals impacted by decaying algae, biodiversity studies of beachcast habitats, accessing the additional benefit of beach wrack removal by taking out excess nutrients and harmful substances from the environment.

Staff involved: Siedlewicz G., Kotwicki L., Szubska M., Korejwo E., Grzegorczyk K., Walecka D., Bełdowski J., Bełdowska M., Graca B., Staniszewska M

Case study partner – FERTIWRACK: Department of Water and Wastewater Technology, Faculty of Civil and Environmental Engineering, Gdańsk University of Technology

Location of the case study: Swarzewo, Poland

Aim of the case study: To transform beach wrack into fertiliser or structure-forming material using natural based solution – reed bed system.

Test/research done: Quality of raw beach wrack, quality of material treated in the reed bed system as well as the quality of reject water from the system

Staff involved: Kupczyk A., Kołecka K., Gajewska M.

The Chapter presents two Case Studies, the more theoretical one (WAIT) and the more practical one (FERTI-WRACK), which were fulfilled in Poland in close relation to each other and focused on the same study area.

Authors: Kupczyk A., Kołecka K., Gajewska M., Siedlewicz G., Szubska M., Grzegorczyk K., Walecka D., Kotwicki L., Bełdowski J, Bełdowska M., Graca B., Staniszewska M.

6.1. Location and geographical description

Almost 500 km of the Polish coastline are characterised by sandy sediments practically without any vegetation. The only exception is the Puck Bay, the shallow area of the Gulf of Gdansk, and in particular an area located near the town of Puck. These waters should be considered as the most productive area along the entire Polish coast. For this reason, two closely located beaches, managed in Puck and unmanaged in Rzucewo, have been selected for Case Studies 6a and 6b (→ Fig. 6.1). The model facility of the reed bed system (case study 6b) was built in the area of the Wastewater Treatment Plant in Swarzewo.

Puck Bay creates specific Baltic micro-habitats, e.g., low salinity, the high influx of freshwater from rivers and groundwater sources [Kotwicki et al., 2014]. According to the scale developed by [Brown & McLachlan, 1990], the beaches in the Puck Bay area are intermediate with medium to fine sand. The swash water salinity ranges from 3 to 8 PSU, and its temperature varies seasonally from 0 to 25 °C. The macrophytic community is more abundant than in other Baltic Sea parts [Kruk-Dowgiałło, 1996].

Figure 6.1: Localisation of sampling place [source: google map view]

6.2 Beachwrack – theoretical background

Beach wrack occurs naturally, practically on all beaches worldwide, including the Baltic beaches in Poland. The material of beach wrack is washed ashore by wind, waves and tides. Retreating waves can also transport them back into the water system [Macredie et al., 2017]. The occurrence of beach wrack supports various small organisms and microbes. It also provides important habitat for invertebrates and shorebirds (food, shelter, nesting). Beach wrack is also essential in protecting the shoreline; it constitutes a physical barrier that dissipates the wave energy (reducing its impact force). Beach wrack contributes to reducing the erosion processes in winter. Seagrass has got fibrous composition which allows us to bind the drifter sand and strengthen coastal dunes. On the other hand, decaying macroalgae were also identified as sources of nutrients and heavy metals (Hg), and other pollutants concentration in coastal sediments. Concerns about beach wrack polluting beaches have led to research into its removal and industrial processing.

6.3 Beach wrack as a problem

Drifting algal mats have recently become a problem in shallow, eutrophic seas worldwide. On the one hand, the excess organic matter washed ashore or deposited on the seabed enhances the growth rates of suspension feeders. On the other hand, it can create local hypoxia events followed by changes in zoobenthos abundance, species composition and food web. Marine plant detritus plays an essential role in the global carbon cycle and exceeds three-fold the amount of carbon stored in living marine plants. Coastal marine waters are the critical areas of plant detritus production and storage. Owing to their permeability, sandy shores are very efficient converters of organic matter. It is necessary to know about detritus production and its biomass to understand the importance of sandy shores in organic matter turnover [Kotwicki et al., 2005].

Furthermore, beach wrack constitutes not only an environmental problem but also a socio-economic problem. The material accumulated on the seashore is not an aesthetic sign. Besides, the process of its decomposition is accompanied by an unpleasant smell. Therefore the adverse consequence

	MANAGED BEACH	UNMANAGED BEACH AREA	
	Puck	Rzucewo 1	Rzucewo 3
Beach [m]:	100 × 13	100 × 3-15	100 × 2
Beach wrack coverage [%]:	1 - 2	8 - 89 (37)	10 - 100 (47)
Beach wrack area [m²]	1 - 54 (25)	32 - 966 (312)	10 -153 (70)
Thickness [cm]	1	1-38 (15)	1 - 14 (6)
Volume [m³]	0.1 - 0.5	3 - 203	1 - 23
Weight [kg/m² ww]	0.1 - 1.1	1.8 - 168	8 - 400

Table 6.1: Calculated values of basic parameters for the studied areas
**in brackets average values*

of beach detritus for coastal tourism is obvious [Balance et al., 2000, Malm et al., 2004]. As a result, it is a severe problem for the local authorities of seaside resorts, where the economy is based mainly on the tourism industry. Beach wrack can also be a potential point source of environmental contamination. Both filamentous algae and higher plants accumulate chemicals from seawater and to some extent, sediments. Existing studies show that in the case of heavy metals algae are enriched in, i.e. mercury and cadmium [Beldowska et al., 2015, Franzen et al., 2019], especially in comparison to concentrations usually encountered in the sandy beaches.

6.4 Beach wrack quantity and composition (the results from WAIT)

Case study 6a included an assessment of beach wrack quantities and analysis of beach wrack chemical and biological composition, and calculation of depuration rate from pollutants, resulting from the removal of organic beachcast from the beaches. Field studies were conducted monthly throughout the year. The deposited organic matter/beach wrack material was analysed in terms of quantity and quality. Chemical analyses included basic environmental parameters, nutrients, organic pollutants, heavy metals, and other harmful compounds. Also, macro- and meiofauna samples were taken, the rate of decomposition of organic material was estimated, and the amount of litter on the beaches was calculated.

Dominant species in beach wrack material practically all year round were higher plants: *Potamogeton pectinatus* and seagrass *Zostera marina* with no significant differences between sites in qualitative terms. On the other hand, concerning the coverage expressed as a percentage or per square meter value and the thickness of the beach wrack, the calculated total volume and weight of the material deposited on the unmanaged beach was many times higher, with values reaching several hundred kilograms per square meter of the beach (→ Table 6.1).

Macrofauna organisms were numerous in both areas. However, the managed beach was characterised by the higher biodiversity and number of species. Higher total biomass was observed in the unmanaged area, but this was due to opportunistic species adapted to live in various unfavourable environmental conditions. The insect larvae chironomids and benthic oligochaetes are examples of such species.

As far as garbage on the beach is concerned, the managed beach was more than twice as polluted with plastic. This is not a surprise, due to the touristic character of the place. The litter count for both sites was the largest in June-July 2019, in the middle of tourist season, and gradually decreased later. The most frequent items were polystyrene/plastic pieces. And in case of the managed beach in the summer season, those were glass bottles and empty aluminium cans. Throughout the year, over 700 items were found in Puck and nearly 300 in Rzucewo. The total weight of the litter found in Puck and Rzucewo was 3.05 kg and 3.77 kg respectively. In Puck, there was mainly touristic litter (plastic cutlery, cigarette butts, etc.) while in Rzucewo the litter consisted more of household goods and building construction litter.

6.5 Chemical contents in beach wrack (the results from WAIT)

In the presented case study 6a beach wrack, sediments and water were investigated for the presence of heavy metals, methylmercury, nutrients,

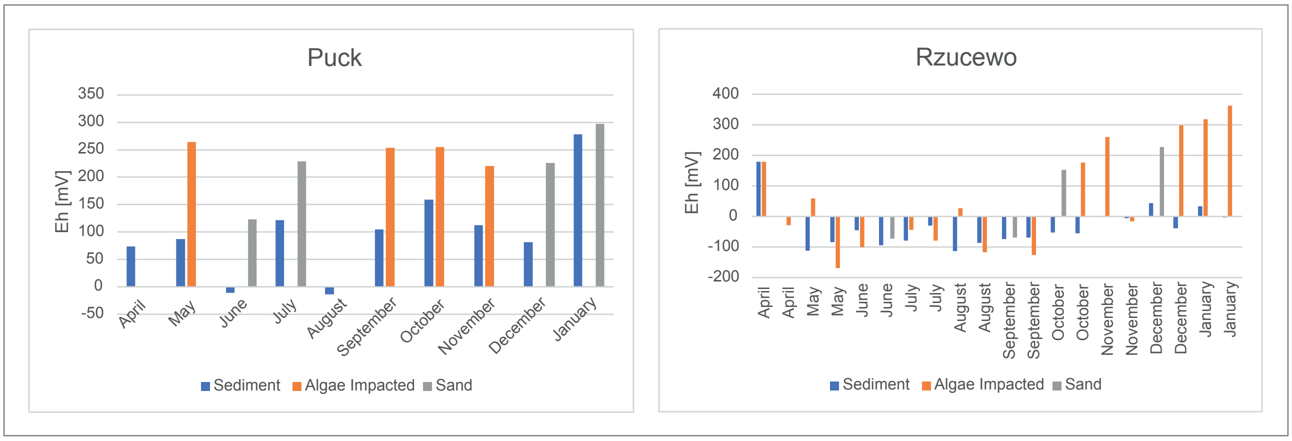


Figure 6.2. Change of the redox potential [Eh] for managed (a) and unmanaged (b) sites

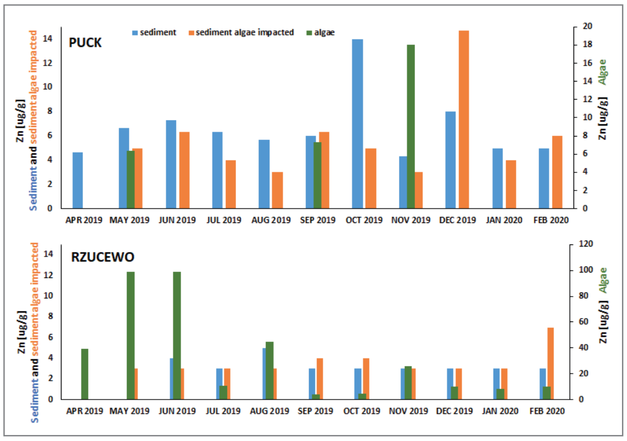


Figure 6.3. Zinc concentrations from in situ measurements in sediments with and without the impact of algae on managed (PUCK) and unmanaged beaches (RZUCEWO)

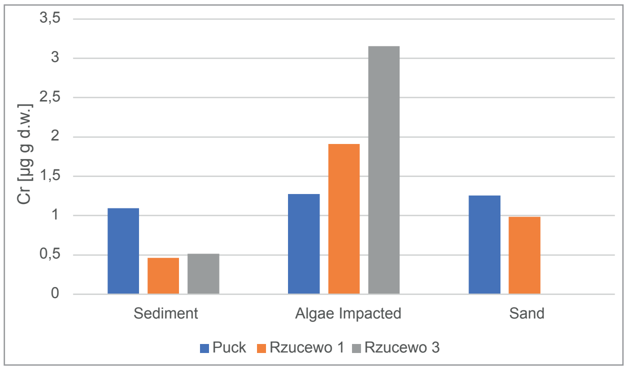


Figure 6.4. Chromium concentrations in sediments with and without the impact of algae in managed (PUCK) and unmanaged beaches (RZUCEWO) in July 2019.

Bisphenol A (BPA), Nonylphenols (NP), octylphenols (OP), Polycyclic aromatic hydrocarbons (PAHs,) and Polychlorinated biphenyls (PCB).

Redox potential. One of the important factors measured during the sampling campaign was the redox (oxidation-reduction) potential. Redox reactions are essential to major element cycling to many sorption processes, to trace element mobility and toxicity, to most remediation schemes, and to life itself. The in situ measurements in surface and pore water show significant oxygen depletion in the warm period and lower annual oxygen levels in the area impacted by algae (→ Fig. 6.2). Moreover, the measurements' results indicate that oxygen consumption during algae decomposition influences an area more expansive than just that covered with algae wrack, resulting in oxygen depletion in pore waters not directly impacted.

Heavy metals are natural elements of the Earth's crust, but their discharge to the environment due to anthropogenic activity overwhelms their natural concentrations. The most toxic heavy metals that pollute the Baltic Sea include mercury (Hg), cadmium (Cd), arsenic (As), and lead (Pb) [Szefer, 2002]. Heavy metals can be toxic even at very low concentrations since they tend to be accumulated in marine organisms and biomagnify along the trophic chain. Consequently, they can threaten final consumers – humans [Zaborska et al., 2019]. The concentration of heavy metals in sediments does not exceed the thresholds values given in Journal of Laws (2002) and HELCOM core indicator.

However, in the case of Zn, one order of magnitude higher concentration was observed in the beach wrack in the unmanaged beach compared to sediments (→ Fig. 6.3).

Also, chromium concentrations are worth further investigations. The observed difference between Cr levels in sand from the managed beach (Puck) and sand impacted with algae (Rzucewo1 + Rzucewo3), as well as sediments from both areas is significant (→ Fig. 6.4). Measured values indicate that an intake of Cr from sediments by algae may occur in the heavily overgrown Rzucewo site (unmanaged

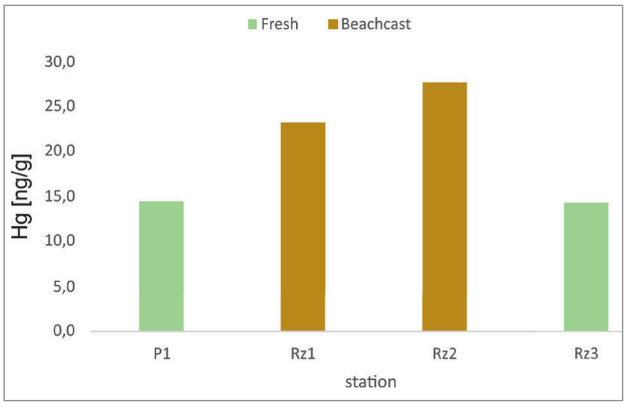


Figure 6.5. Total mercury concentration in live algae at the managed site (P1), decaying beachcast at the unmanaged site (Rz1, Rz2) and live algae at the unmanaged site (Rz3)

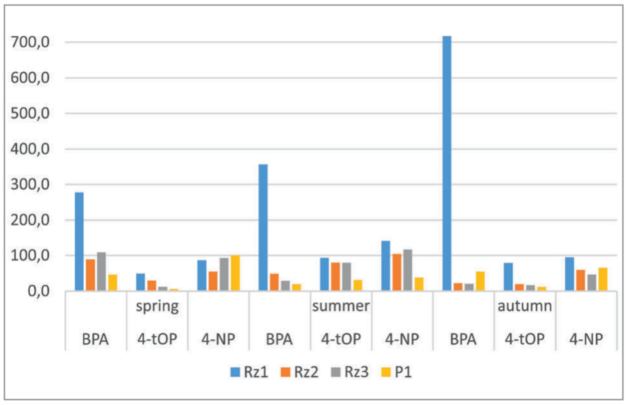


Figure 6.6. Concentrations of bisphenol A (BPA), 4-tert-octylphenol (4-t-OP) and 4-nonylphenol (4-NP) ng.g-1 dw in microalgae depending on season and station

site). Afterwards, the element can be transferred to the beach sand due to wracked algae decomposition. Although the chromium data are only available for one sampling campaign (July 2019), the preliminary results suggest that beach wrack can be a source of metals to the coastal environment.

Methylmercury (MeHg) is the most toxic and dangerous form of mercury occurring in the environment. MeHg is highly bioaccumulative in organisms and undergoes biomagnification via the food chain. The environmental conditions promoting methylation processes and production of MeHg are anoxic conditions, high contents of organic matter, and specific microorganism. All of those conditions are present in the beach wrack. Results from the measurements of MeHg in sediments and sand do not give a definite answer if the beach wrack promotes the production of MeHg. For the Rzucewo site (unmanaged site) in June 2019, the highest concentration of MeHg (20 pg g-1 d.w.) was measured in algae impacted beach sand in comparison to the not impacted (8 pg g-1 d.w.) and sediments collected from water (5 pg g-1 d.w.). However, in July 2019 the highest concentration was in sediments collected from water (45 pg g-1 d.w.) in comparison to algae impacted beach sand (6 pg g-1 d.w.) and not impacted sand (<LOD). In case of the managed beach in Puck, both in June and July 2019, MeHg was detected only in sediments at low concentration (8- 10 pg g-1 d.w.), and in the sand from beach concentration was below the detection limit (<LOD).

The mercury concentration (total mercury) on the managed beach (P1), in the sites with algae, is lower than on the unmanaged site, where decomposing wrack was collected (Rz1 and Rz2) (→ Fig. 6.5). However, in the unmanaged site, mercury concentrations in live algae (Rz3) were similar to those at the managed site. This indicates, that although biological material from the bay accumulates Hg at the same rate, and is characterised with the same mercury concentration at both sites, accumulation does not stop after landing. Decomposed material on the beach wrackage site is rich in organic matter and continuously builds up Hg concentration. This is probably caused by excellent sorption capabilities of decaying plant and algae material. It may capture mercury from coastal water, acting as a filter for surf water. This means that unmanaged beaches may transfer mercury from beachcast via accumulation in live algae and subsequent release, therefore enhancing mercury flux to the beach from local sources. Analysis of depth profiles indicated that mercury is released from beachcast into the groundwater of unmanaged areas.

Bisfenol A (2,2-bis-(4-hydroksyfenylo)propan - BPA), 4-tert-oktylofenol (4-t-OP) and 4-nonylofenol (4-NP)

Bisphenol A and 4-nonylphenol were identified in all kind of samples, the 4-tert-octylphenol in some samples was not detected (especially in microalgae from July and in water from November). The highest concentrations were observed for BPA in pore water (avg. 6,000 ng.dm-3) or pore water under algae (avg. 400 ng.dm-3), macroalgae (avg. 214.3 ng.g-1 dw[1]) or sediments (avg. 2.9 ng.g-1 dw). It was a noticed enrichment in pore water or pore water under algae compared to surface water (the concentration ranging from several-fold increase

1 dw – dry weight

STATION	C	N	P
P	298	21	1
Rz2	406	25	1
Rz3	421	23	1
Rz1	559	33	1

Table 6.2. Molar ratio of C:N:P in wrack at stations P, Rz1, Rz2 and Rz3

to 67 times higher) for all phenols. Concentrations of phenols depending on season and site were the most noticed for microalgae (→ Fig. 6.6). The maximal average concentration of microalgae for the site was achieved on station Rz1 (BPA – 450.7; 4-t-OP – 74.1 and 4-NP – 107.8 ng.g-1 dw), the lowest one – for the references station P1 (40.6; 16.6; 68.5 ng.g-1 dw respectively). These concentrations were the highest for autumn.

Carbon, nitrogen, phosphorus and water-extractable forms of phosphorus and nitrogen in beach wrack

Forty-six beach wrack samples collected from April to November at 4 stations were analysed.
Usually, at all stations within a given month, total carbon Ctot), total nitrogen (Ntot) and total phosphorus (Ptot) content in detritus decreased as follows: the wrack from the water was characterised with the highest concentration of studied elements, the wrack from a surface layer of beach sand contained slightly lower concentrations, while wrack buried beneath a layer of beach sand showed the lowest concentration. This reflects the gradual decomposition of organic matter after its deposition to the beaches. The exception was the R1 station, where wrack was the most degraded as indicated by the highest value of the C: N: P ratio (→ Table 6.2), and relatively low concentration of water extractable forms of nitrogen (N-NH4) and phosphorus (P-PO4) (→ Fig. 6.7). Detritus probably lingers on the beach for a long time in this area. Generally, wrack accumulated at unmanaged beaches (Rz1, Rz2, Rz3) was more decomposed in comparison to wrack from the managed beach (P) (→ Table 6.2).
Rough estimation show, that in beach wrack accumulated along 100 m of the coast (mean dry wet) at unmanaged stations (Rz1, Rz3), the weight of phosphorus ranged from 18 to 36 kg (→ Fig. 6.8). Considering that the phosphorus concentration (median) in algae samples classified as living is known, it can be roughly calculated, that such a load delivered to the seawater could be responsible for producing 6 to 29 tonnes of phytoplankton biomass (→ Fig. 6.8).

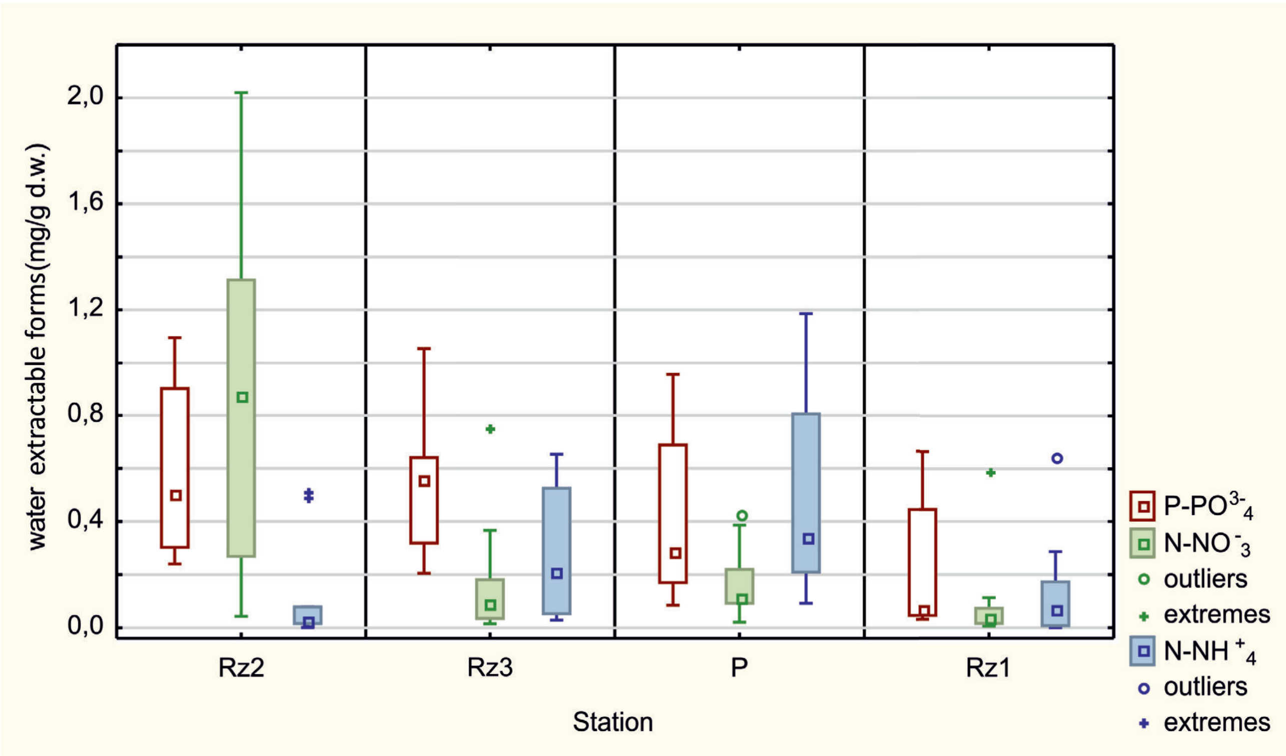


Figure 6.7. Seasonal and spatial variability (a) carbon (Ctot), (b) nitrogen (Ntot) and (c) phosphorus (Ptot) in wrack sampled from surface water and two layers of beach sediments at three stations.

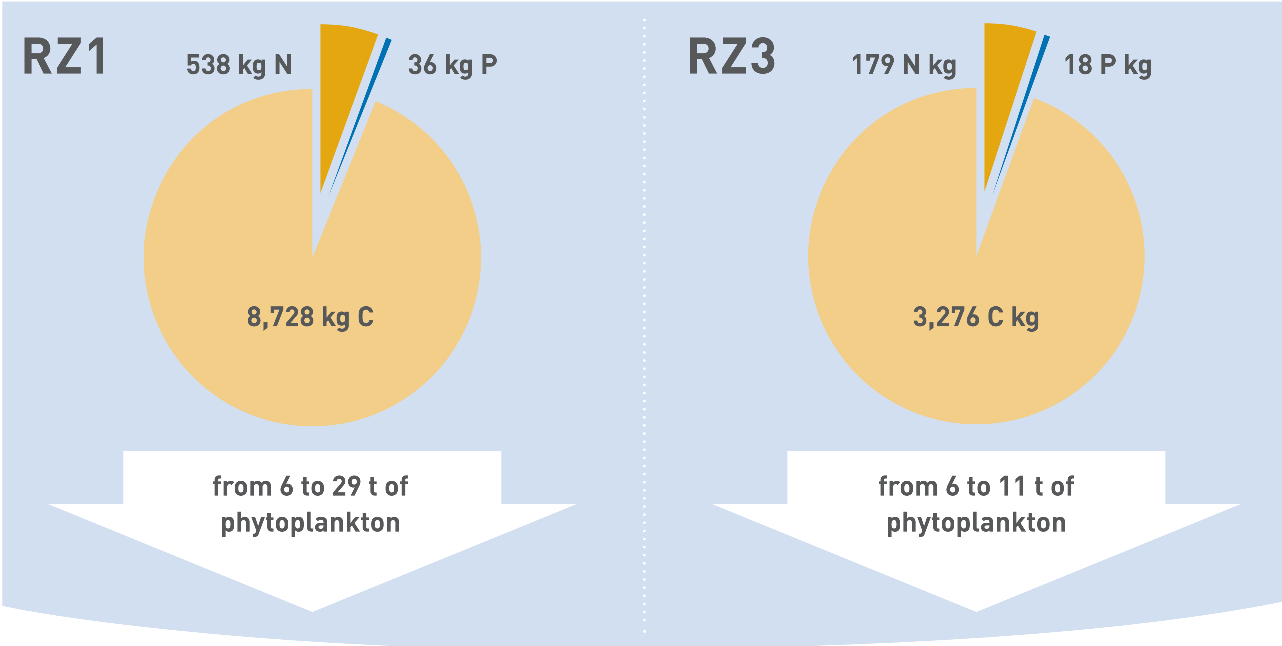


Figure 6.8. Mean load (kg) of phosphorus, nitrogen and carbon accumulated at 100 m of unmanaged coast (station Rz1 and Rz3) and potential production of phytoplankton biomass (assuming total decomposition of beach wrack and P limitation).

6.6 Technology tested

To transform beach wrack from nuisance to resource, the Gdańsk University of Technology, (under CONTRA case study 6b FERTIWRACK), has tested the possibility of a reed bed system used to obtain fertiliser from beach wrack as a final product.

The reed beds are commonly known for the treatment of different kinds of sewage sludge. The average system works 8-12 years, but it can be extended up to 15 years. The operation time consists of start-up time, full operation time and system emptying periods [Kołecka, 2019]. The basic principle of reed systems operation is based on the use of processes naturally occurring in wetland ecosystems in controlled environmental conditions [Gajewska, 2019]. Model facility (→ Fig. 6.9, foto → Fig. 6.10) was built at the Wastewater Treatment Plant in Swarzewo in autumn 2019. The beach wrack material was collected on the beach in Rzucewo and cyclically fed into individual parts of the deposit. Material charging was done manually and carried out by an authorised person.

First, the discharging of beach wrack took place in October 2019. Then the pilot system rested for 5 months. In April 2020, the Gdańsk University of Technology's research team began to regularly discharge beach wrack material into the reed bed system's pilot plant installation at the WWTP in Swarzewo. Changes in the reed bed system's material after one month of operation are presented in → Fig. 6.11.

Each month, the beach wrack collected for research was at a different decomposition stage, reflecting its basic parameters (→ Fig. 6.12). The water content ranged from 94.6 % (July) to 95.5 % (June), the content of the mineral substance – from 43.9 % (June) to 58.6 % (July), and the organic substance content – from 41.4 % (July) to 56.1 % (June). The higher the mineral substance content was registered, the higher the algae decomposition rate was observed. Changes in the material are presented in → Fig. 6.13. The bed material is dewatered (→ Fig. 6.14) and subjected to a stabilisation process (→ Fig.

Figure 6.9. Scheme of pilot reed system based on cubic modules [A. Kupczyk's study]

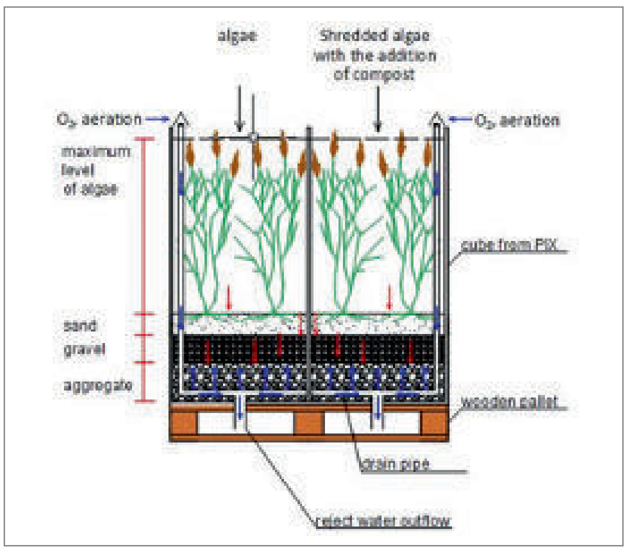


Figure 6.10. Constructed pilot plant of RBS at WWTP in Swarzewo: (a) reed in the RBS (August 2020), (b) two cubic pilot plant RBS (October 2019), photo: A. Kupczyk

Figure 6.11. Constructed pilot plant of RBS at WWTP in Swarzewo: (a) reed in the RBS (August 2020), (b) two cubic pilot plant RBS (October 2019), photo: A. Kupczyk

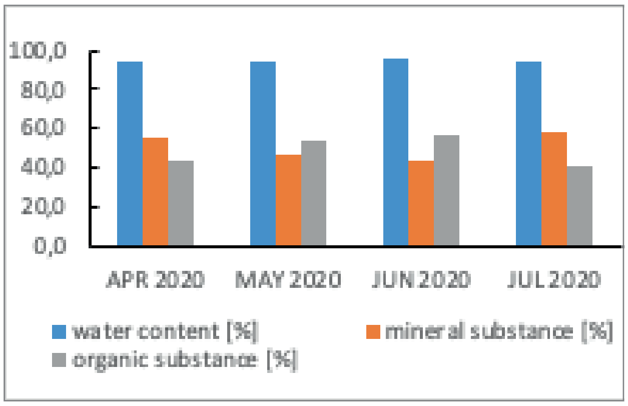


Figure 6.12. Changes in fundamental parameters of collected raw beach wrack in time [A. Kupczyk's study]

6.15), which is indicated by a decrease in the content of organic matter.

One-month changes in the basic parameters of the material discharged to RBS are presented in → Fig. 6.16.

In the case of reject water, it isn't easy to establish a repeatable test scenario. Every month a different amount of reject water from the reed system was collected. The difference depends on the vegetative needs of the reed and weather conditions occurring in that specific month. The quality of reject water and it changes after supply of fresh material to deposit is presented in → Table 6.2.

6.7 Management-related obstacles

The reed bed system is characterised by simple construction but requires proper design and professional performance. The lack of precision in the facility's construction may contribute to the subsequent incorrect operation of the system.

The exploitation time of the deposit is relatively long, but it consists of the start-up period, full exploitation and emptying of the system. The deposit start-up period can last for about 2 years, which can be an obstacle to choosing this method.

The beach wrack material properties are unknown, so it is difficult to determine the appropriate dose and frequency of charges. The system works in an altering cycle. There are two phases of work: (i) irrigation – the supply of raw material and (ii) rest–break in the feeding of deposit. There are no precise guidelines for the time between charges. The intervals between subsequent irrigations will depend on the efficiency of the bed, atmospheric conditions, the age of beach wrack, dry matter concentration in beach wrack and thickness of the layers of accumulated material. More extended periods between the next irrigations may result in better dewatering and stabilisation efficiency.

Also, the reed bed system, depending on the forecast amount of beach wrack material that will be

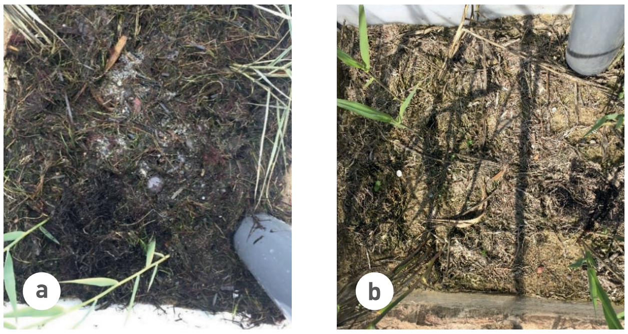


Figure 6.13. Beach wrack material in the reed bed system: (a) Test supply of beach wrack to RBS, 18 November 2019 [photo: A. Kupczyk], (b) beach wrack in RBS after 6 months, on 27 May 2020. Photo – A. Kupczyk

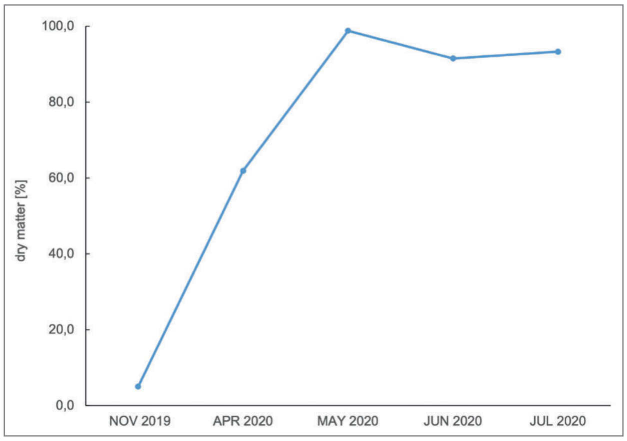


Figure 6.14. Changes in dry matter content in beach wrack material (without fresh discharging [A. Kupczyk's study]

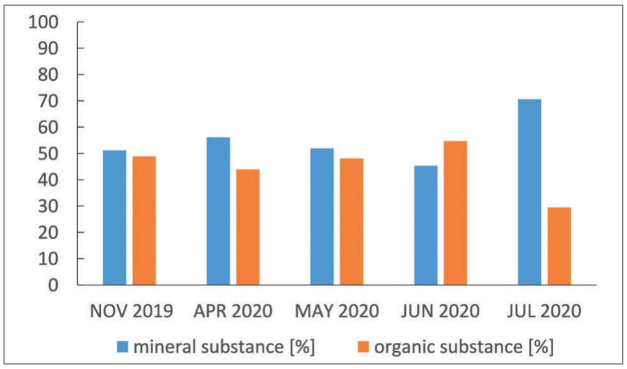


Figure 6.15. Changes in mineral and organic substance in beach wrack material (without fresh discharging) [A. Kupczyk's study]

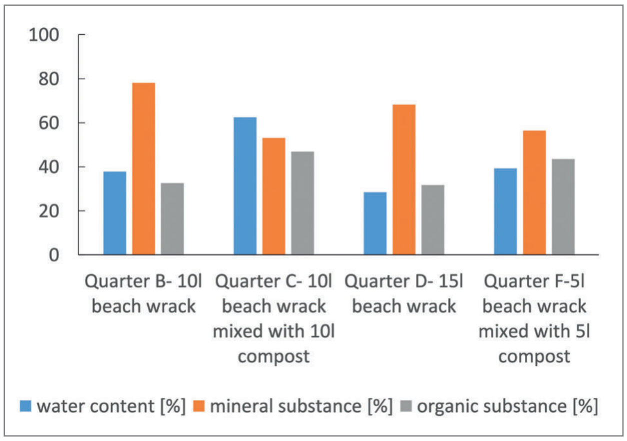


Figure 6.16. Changes in basic parameters in material discharged in RBS after one month of treatment (average value from 3 months) [A. Kupczyk's study]

processed in the system, may require significant space, which entails the financial problem of purchasing land for the construction of the facility.
Another problematic aspect may be the location, which should be relatively close to the beach wrack collecting point. This material contains significant amounts of water, which increase mass and volume, and therefore transportation costs. For this reason, a neighbourhood of the beaches should be considered as a construction site for a reed bed system.
Another problem may be a manmade waste, including plastics found in the collected beach wrack material. Using a reed bed system for beach wrack processing assumes high-quality fertiliser production, and wastes are not a desirable component of fertilisers. There is a pre-selection problem that must be carried out before serving the beach wrack on the bed.

6.8 Administrative/legal obstacles

The definition of "beach wrack" currently does not exist in the European Union legal system. Therefore, it should rely on the "composition of beach wrack" and similar existing definitions. The nearest term for beach wrack in Poland is "kidzina".

Council Directive 92/43 / EEC of 21 May 1992 on the protection of natural habitats and wild fauna and flora prohibits the destruction of the natural environment of "kidzina" on the seashore [Armknecht et al., 2020]. However, according to the European Union Directive on the bathing water quality (2006/7 /EC), the beach management authorities are responsible for removing macroalgae accumulating on the coast [Kupczyk et al., 2019]. Entities responsible for beach management choose cleaning companies, without distinction for what happens with the collected material. They only indicate that it is to comply with the law. This contributes to the inefficient use of beach wrack material [Armknecht et al., 2020]. Following with Directive of the European Parliament and of the Council (EU) 2018/850, the algae is biodegradable waste. It is prohibited to store this kind of material at landfills, so they must be disposed of [Kupczyk et al., 2019]. The Act of 27 April 2001 – Environmental Protection Law (Journal of Laws of 2019, item 1396, as amended)

	PH	COD	TN	TP	N-NO2-	N-NO3-	N-NH4+	PO43-
	[-]	[mg O2/l]	[mg TN/l]	[mg TP/l]	[mg NO2/l]	[mg NO3/l]	[mg NH4/l]	[mg PO4/l]
RW before supplying of BW	8.06	161.00	47.10	0.56	0.08	29.80	0.07	0.32
RW after BW supplying	8.01	258.00	91.40	0.89	0.13	54.80	0.35	0.46
RW after months of supplying	7.85	816.00	40.10	0.36	0.51	12.60	0.57	0.25
Sea water	8.07	81.00	3.69	0.56	0.01	0.15	0.04	0.31

Table 6.2. The quality of reject water (RW) and its change after the supply of fresh material of beach wrack (BW) to deposit

gives consent for "disposing of waste to inland waterways surface and underground waters, internal marine waters or territorial sea waters." for a much higher fee than for storing waste at a landfill [Armknecht et al., 2020].

6.9 Proposals for potential solutions basing strongly on the case study

The reed bed system solution is an option that can be used by local authorities responsible for beach management. It's also a potential idea for companies, which take part in beach cleaning.

Besides, this solution fits in assumptions of a circular economy and change beach wrack into a resource (fertiliser). This gives the possibility of reintroducing nutrients into the matter cycle and allows reusing these compounds in a place where they are desirable. The reed bed system is an environmental solution. As mentioned above, its operation is based on natural processes without introducing new substances to the environment. This solution has a low carbon and water footprint. Both aerobic and anaerobic processes in the reed bed system contribute to forming carbon dioxide (product of oxygen processes) and methane (product of anaerobic processes). Due to the mineralisation process, the production of greenhouse gases is inevitable. Still, a well working system decreases the amount of methane produced to a minimum and supports methane oxidation by aerobic methanotrophic bacteria.

6.10 Conclusions

Results of contamination analysis show that concentrations of some pollutants, like metals or organic compounds in the beach wrack, can affect the environment. The preliminary results suggest that beach wrack can be a source of zinc and chromium to the coastal environment. Moreover, specific conditions, like low oxygen concentration and high redox potential, can foster the release of contaminants from beach wrack (BPA). Preliminary results also show that beach wrack conditions can initiate a transformation of some elements, e.g. mercury (Hg) to more toxic compounds like methylmercury (MeHg).

Regarding the contaminants in the beachcast, in most places, concentrations are below thresholds preventing their commercial use. However, local hotspots appear to exist in the case of some compounds, i.e. cadmium in seagrass in Gotland. This phenomenon may restrict some utilisation options, but not all, in particular regions. Therefore, specific case studies are required in some regions, especially those known to have former historic contamination.

The reed bed system seems to be a potential solution in the case of beach wrack nuisance, enabling its conversion into a resource of fertiliser. The reed bed system allows for significant dewatering and stabilisation of beach wrack. The dewatering process is indicated by changes in the dry matter content in the material processed in the bed.

Beach wrack material is a source of nutrients for reed and positively affects its growth, indicating

Figure 6.17. Differences in the condition of reed fed with beach wrack material (a) and not fed (b).

good fertilising properties. Between quarters where it was delivered and the "empty" one (there is a significant difference in reed condition (→ Fig. 6.17).

Also, the reed bed system is an environmentally friendly solution. The system's work is based on natural processes occurring in wetlands, and it takes place without the use of additional chemicals supporters the processes. This solution requires no energy outlays and is characterised by low emission. This fact is an additional advantage of using this solution.

As for the economic aspect of the reed beds, it seems beneficial. The construction of the system does not require large financial outlays due to the simple construction of the facility. When it comes to operating costs, they are also low. Well designed and precisely made reed bed system does not show a high failure. Moreover, no additional chemicals are used, which also reduces the exploitation costs of the system. A potential additional advantage of using the reed bed system for beach wrack processing can be the production of highly nutritious fertiliser, which can become a source of income for the investor.

The transportation of beach wrack material may produce a high cost. If beach wrack is processed far away from the place of collecting, this solution may simply turn out unprofitable. The high water content increases the volume and mass of the collected material, and they are basic factors determining transport costs. The high cost may also be conditioned by the purchase of an appropriate area for the facility's construction.

The use of a reed bed system can also bring benefits to local communities. The first one will be "clean" beaches that tourists will preferably visit. Coastal resorts are struggling with the problem generated by the beach wrack decomposed on the shores – an unpleasant smell and an aesthetic look. Finding the suitable management options and refining the regulations in this matter can contribute to greater interest in given places by tourists, which translates into the profits of the inhabitants who mainly earn on tourism.

Currently, decisions are based on experience from processed sewage sludge, whose properties are well studied. In terms of beach wrack, everything is new. It needs to develop a method from scratch, based on properties and observation of beach wrack material behaviour in the deposit, which is not a simple task.

The main uncertainty of the proposed solution is the end product, i.e. a fertiliser. It's not known, whether its properties meet legal requirements and whether it can be used.

Estonian experience: production of furcellaran both from trawled and beached algae *Furcellaria lumbricalis*

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Location of the study area: Estonia

There is no specific case study in Estonia within the CONTRA project. This chapter presents the Estonian experience related to beach wrack use. It summarises the information regarding the management of rare red algal community (*Furcellaria lumbricalis* and *Coccotylus truncates*) located in the West Estonian Archipelago Sea, Estonia, Baltic Sea. The raw material is collected both via trawling and collection of beached algae and from that furcellaran – an anionic partly sulphated polysaccharide (classified together with carrageenan (E407)) – is produced by the local company Est-Agar AS (www.estagar.ee). Currently studies are carried out to estimate the possibility of also producing R-phycoerythrin (pigment used in the food and biotechnological sectors).

7.1 Location and geographical description

The West Estonian Archipelago Sea (in Estonian: Väinameri) is located in the eastern part of the Baltic Sea in the coastal waters of Estonia (→ Fig. 7.1). It is a hydrologically very active water basin formed by a system of straits connecting the waters of the Gulf of Riga to the Baltic proper and the entrance to the Gulf of Finland. The total surface area of the system is 2,243 km², and the total volume amounts to 10.6 km³ [Suursaar et al.,1998]. This sea area is characterised by its shallow waters: the mean depth of the whole system is less than 10 m with the deepest location at 22 m in the middle of the Suur Strait (between Muhu island and mainland). The salinity varies between 6 and 7 PSU. Sand and sandy clay substrates prevail in the area, harder substrates as gravel or boulders can be found only in the most shallow and wave-exposed areas. Due to the shallowness and the bottom substrate being dominated by fine sediment fractions, water transparency is often very poor. After storm events, the Secchi depth may decrease to 0.5 m, while in the case of prolonged calm weather conditions the photic zone reaches the bottom in about 90 % of this area [Martin et al., 2006, Kotta et al., 2008].

Drifting mats of *Furcellaria lumbricalis* and *Coccotylus truncates* cover soft sediments at depths

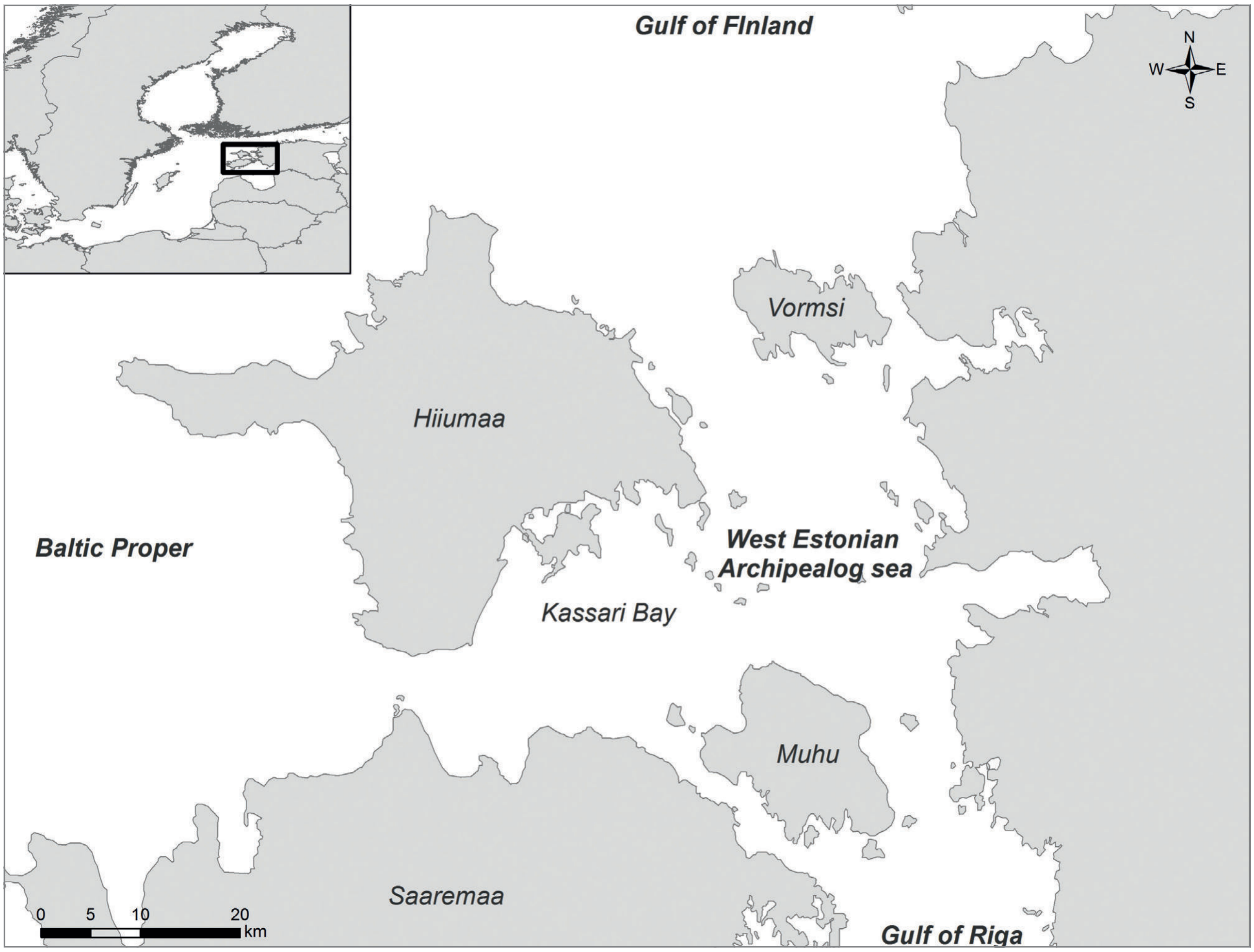


Figure 7.1: Location of the case-study area.

between 5 and 9 m in the subregion Kassari Bay, the community is maintained by the prevailing circular currents and the ring of islets that surround the area [Martin, 2000, Kotta et al., 2008] (→ Fig. 7.2). Similar communities were also present in the waters of Denmark and Poland but were lost due to overexploitation and eutrophication in the period 1970–1980 [Weinberg et al., 2019, Schramm, 1998].

7.2 Description of beach wrack effect as a natural process

In the West Estonian Archipelago Sea, the area of loose-lying algal community has varied within 130-200 km², and the biomass has been estimated between 160 000–260 000 tons in wet weight (in the last 20 years) [Weinberger et al., 2019] (→ Fig. 7.3). The algal mat's average coverage is 70 %, and thickness varies between 5–15 cm. Within the last decade, the areal coverage and biomass values have been relatively stable, around 175 000 km² and 170 000 tons in wet weight, accordingly [Weinberger et al., 2019; Paalme, 2019]. In 2015–2020 the catch suggestions for bottom trawling was 2,000 tons of algae (all species included) in wet weight – representing about 1–2 % of the standing stock [Paalme, 2015, 2017, 2019]. The trawled seaweed contains an average maximum of 8 % additives. In 2019 the number of algae collected via trawling in June and September was 60 tons (https://www.agri.ee/et/eesmargid-tegevused/kalamajandus-ja-kutseline-kalapuuk/puugiandmed). The trawling takes place mostly in the period April-June.

The amount of algae lost via beach cast is estimated at 4,800 tons of wet weight [Kersen&Martin, 2007]. The beached material, both attached and unattached forms of *F. lumbricalis*, is also collected by locals, dried in the sun, and sold to the company. The weather conditions vary a lot annually, but usually, the algae are washed ashore during autumn storms, after which the algae is collected and laid on the fields for wintering. In spring- and summertime the algae is dried in the sun (as hay), compressed into bales, and transported to the company. The company Est-Agar AS takes samples to estimate the share of *F. lumbricalis* within the dried algae; the preferred share is over 80 % (the cleaner

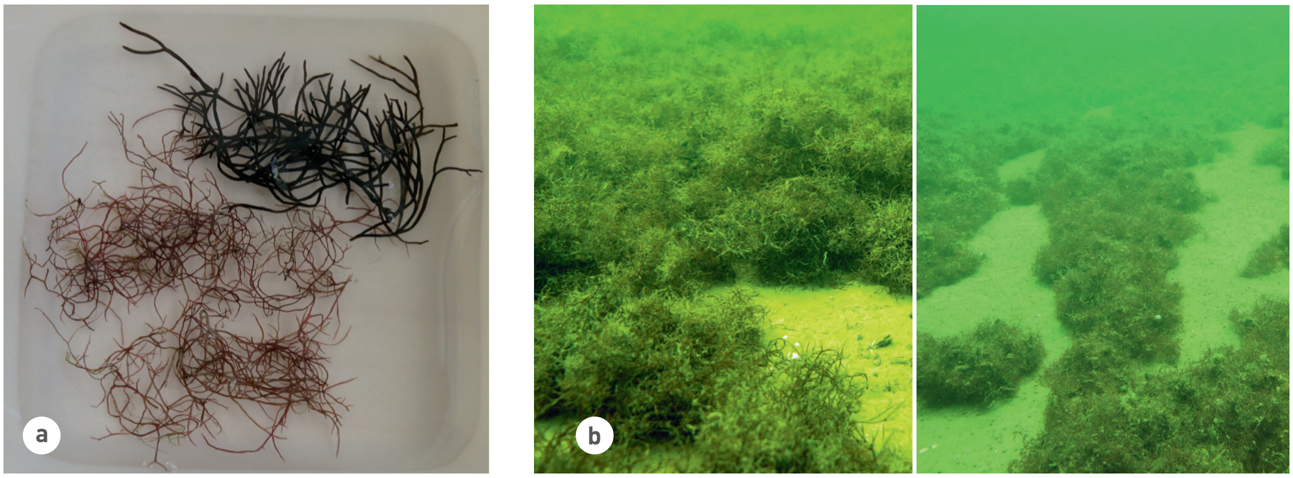


Figure 7.2: Dominating algal species in the Kassari Bay loose-lying algal community (a): A – *Furcellaria lumbricalis*, B – *Coccotylus truncates* (re-drawn from [Paalme, 2017]); loose-lying algal community in the Kassari Bay (b), closer look (Photo: G. Martin).

material is indeed preferred). In 2020 the company bought in a total of 300 tons of sun-dried *F. lumbricalis*. The price for 1 ton has been fixed at 350 EUR (VAT not included) in the latest years, and some families have gathered the beached algae for several generations. At the moment, there are about 20-30 people who actively collect the beached material across Saaremaa.

7.3 Why beach wrack is a problem?

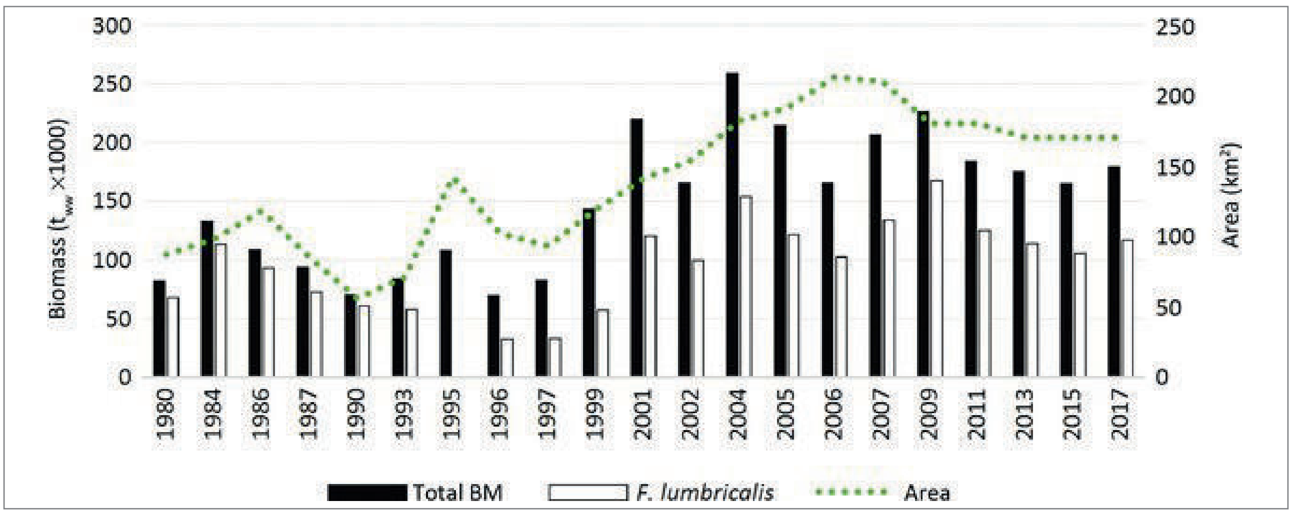
The beach wrack itself is not a problem at the coast of the West Estonian Archipelago Sea, as there are no long and sandy beaches that would be of tourism interest and addressed to beach cleaning. Due to the Kassari Bay's specific conditions, the primary beached algae are *F. lumbricalis* and *C. truncates*, and the beach wrack is seen as a resource and option. The use of beached algae helps to optimise trawling activities and keep the resource to remain its natural reproduction rate.

7.4 Technology recommended

Gathered material is dried and stored having a maximum of 22 % moisture content. It is kept in storehouses until further use. Furcellaran is extracted from raw seaweed *F. lumbricalis*, and the liquid extract is purified by filtration. The liquid extract may be converted into flaky furcellaran by evaporation of water to yield by drum drying. Proper release of the dried material from the dryer roll requires adding a small amount of roll-stripping agents (food oil). (Estagar 2020) (→ Fig. 7.4). For the production of 1 kg of furcellaran it roughly takes 20 kg of dried *F. lumbricalis.*

Also, the furcellaran can be isolated from the liquid extract by precipitation of the furcellaran with

Figure 7.3: Interannual variation (1980–2017) of the total community biomass (BM), the total Furcellarialumbricalis biomass, and the area of the loose-lying red algal community in the Kassari Bay, West Estonian Archipelago Sea (re-drawn from [Weinberger et al., 2019]).



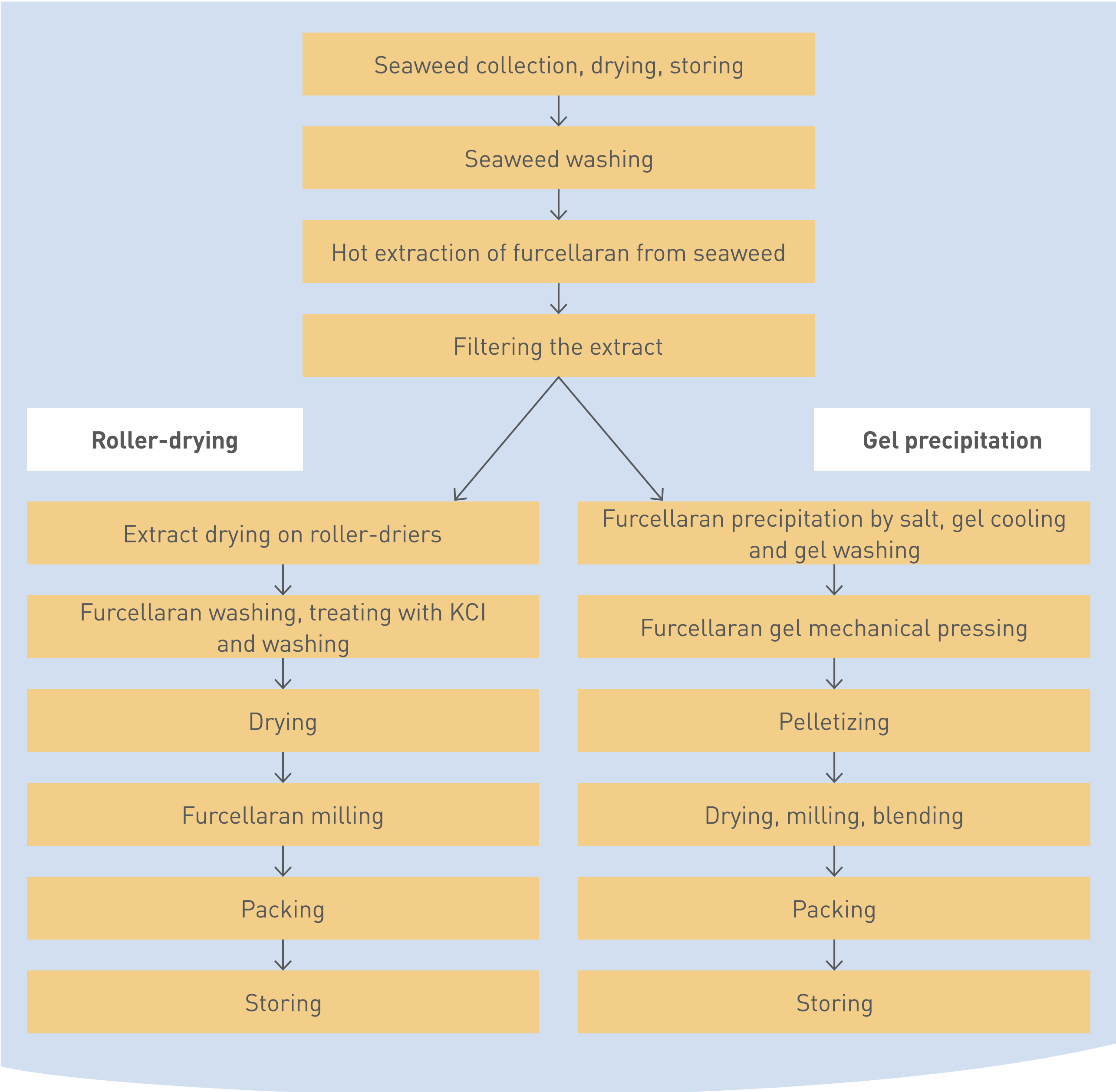


Figure 7.4: Manufacturing options of raw material (re-drawn from [Estagar, 2020])

potassium chloride. This process gives a pure and concentrated product. (Estagar 2020) (→ Fig. 7.4).
The growing interest towards the furcellaran and late, the red pigment R-phycoerythrin that can be extracted from red algae, e.g. *F. lumbricalis*, and *Ceramium tenuicorne* [Tuvikene&Robal, 2015b, Kersen et al., 2017] has brought more interest to the land-based cultivation systems. One of the cultivation methods was tested under the project "Development, testing and evaluation of intensive cultivation technology for production of an unattached form of *Furcellaria lumbricalis*" (07/2017 – 31/12/2019, funded by European Maritime and Fisheries Fund) which gave valuable input for the species biology, and cultivation technology can be developed further to meet the suitable conditions for algae [Paalme, 2020].

7.5 Management-related aspects/obstacles

The company Est-Agar AS has been working for quite some years already and has overcome most of the obstacles during its everyday activities. Updating the technology, machinery, and discovering new possibilities for extracting more substances from algae are directing the company's progress at the moment.

7.6 Administrative and legal aspects/ obstacles

In Estonia, the community of *F. lumbricalis* and *C.*

truncates has been harvested via bottom trawling since 1966 and beach cast collections since 1976 together with official regulation on a national level and regular monitoring of the status of the resource [Martin et al., 1996]. According to the Estonian Fishing Act (2016), the *F. lumbricalis* in the sea is in the ownership of the state, and *F. lumbricalis* washed ashore is in the ownership of the owner of the immovable property located on the shore. Regular monitoring is carried out in the period of July-August (end of active vegetation period of dominating algae) and biomass, coverage, and share of *F. lumbricalis* compared to other dominating species (*Coccotylus truncates*), other macroalgal and zoobenthos species are estimated [e.g. Paalme et al., 2017]. Based on the monitoring results, the suggestions for catchment amounts and regions are given. Since 2007 the monitoring of the status of the algal community has been carried out once in 2 years, and the catchment suggestions are also given for a maximum of two years.

With the growing need for furcellaran and R-phycoerythrin, the company Est-Agar AS also plans to start growing algae on its own, and this is where the legislation is missing at the moment, and it's being worked out.

7.7 Proposals for potential solutions

Close contact with research institutes and policy-makers is suggested. The company Est-Agar AS has been involved in working out legislation for farming and the cultivation of algal species in Estonia since 2018.

7.8 Conclusions

Some of the key messages regarding the experience with *F. lumbricalis* harvesting (both trawling and collection of beach wrack) and management in Estonia are:

- the need for official regulation of the algal material (resource) on the national level. *F. lumbricalis* is so far the only separately legislated algae in Estonia, and according to the Estonian Fishing Act the *F. lumbricalis* in the sea is in the ownership of the state, and *F. lumbricalis* washed ashore is in the ownership of the owner of the immovable property located on the shore;
- the need for regular monitoring of the status of the algal community/resource – depending on the interests, but annual/biannual monitoring would be suggested. Due to trawling activities, it is most crucial to estimate the status of the algae and adjust catchment accordingly as the species are also vulnerable to changes in hydrological conditions;
- care for sustainable management on an enterprise level and close contact with research institutions. Through times, there has been one company that has been in charge of catching and producing the *F. lumbricalis*, and they have managed the resource responsively;
- algae cultivation is one possible solution to maintain a continuous flow of the raw material.

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