SEAGRASS:
POSSIBLE CAREER OR WASHED UP?

Literary review on properties and possible applications of Zostera marina and Posidonia oceanica

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October 15, 2021

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EXECUTIVE SUMMARY

Two seagrass species, *Zostera marina* and *Posidonia oceanica,* are primarily found at European coasts. Seagrass meadows supply important ecosystem services such as: providing shelter to marine life, producing oxygen and filtering seawater. Although, at the end of their life span, seagrass leaves detach and wash up on coastlines as seagrass wrack. Beach wrack is often removed on recreational beaches to keep them attractive for tourism. However, the management of this waste stream incurs in high costs for coastal authorities and is not ideal as it is most often landfilled. ArtEZ Future Makers, in collaboration with designers Conny Groenewegen and Marijke Bruggink, research the possibilities to use this seagrass wrack for various applications. This consultancy project identified the biological, chemical, and physical properties of seagrass wrack from both European species and the applications that could derive from them. Additionally, it was assessed how growing conditions and environmental factors affect seagrass properties and the environmental implications of using this material as a resource. It was concluded that washed up seagrass could be utilized in plenty of traditional and novel ways, including compost, mattress filling, building materials and biochar production. Although, using this resource as a material also has its challenges. The commissioner should consider the temporality of leaf shedding, geographical distribution, local legislation and adequate processing according to a specific application. By using washed up seagrass as a resource, ArtEZ Future Makers matches European Union’s Circular Economy goals and can create awareness of the ecological and economical importance of this marine plant.

VOCABULARY

Annual: populations that live only for one year

Aegagropiles: *spherical agglomerates that appeared on the beach after forming when part of dead P. oceanica roll in shallow water by hydrodynamics (Boudouresque et al., 2012).*

Annelids: *Ringed worms / segmented worms*

***Anaerobic digestion**: process in which bacteria breaks down organic matter in the absence of oxygen*

Anthropogenic: *Originating from human activity.*

***Banquettes**: deposits formed from* seagrass leaves that accumulate on European shores

Biochar: *a charcoal made from the thermochemical conversion of plant and animal biomass* in an oxygen limited environment (Macreadie et al., 2017)

Crustaceans: *Arthropod taxon that includes crabs, lobsters, crayfish & shrimps*

Detritus: *Dead organic material*

***Epiphytes:** an organism that lives on the leaves of a plant*

Gastropods: *Snails and slugs*

Global Warming Potential: *measurement developed to allow comparisons of the global warming impacts of different gases, as each gas has different effects in the Earth's warming. For instance, a ton of methane (CH_4) is estimated to have a 28-32 higher Global Warming Potential than a ton of carbon dioxide (CH_2)*

Greenhouse gas (GHG): a gas that absorbs and emits radiant energy causing the greenhouse effect in the Earth. It includes H_2O, CO_2, CH_4, N_2O and O_3.

Hydrodynamic forces: Forces exerted on a plant through the movement of water. E.g. waves or strong currents.

Hydroscopic: readily taking up and retaining moisture

Intertidal: Refers to an area or lifestyle that is above water level at high tide and below water level at low tide

Interfibrous tissue: Refers to tissue that is located between plant fibers and, as a consequence, is low in lignocellulosic material

Lignocellulosic: plant dry matter from the cell wall consisting of hemicellulose, lignin and cellulose.

Oligo-elements: bio elements present in small amount in living beings. Their absence or excess can be harmful for organisms

Perennial: populations that have a lifespan of more than one growing season

Subtidal: Refers to an area or lifestyle that is below water level even at the lowest tide

Terpenoids: organic chemicals derived from the 5-carbon compound isoprene, and the isoprene polymers called terpenes

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1 INTRODUCTION

1.1 BACKGROUND & PROBLEM STATEMENT

Seagrass is a marine vascular flowering plant that has evolved from freshwater plants over three to four separate lineages, resulting in a total of around 60 species within 12 genera (Borum et al., 2004). In Europe, mainly two species of seagrass can be found, *Z. marina* on the Baltic and North Sea coast and *P. oceanica* on the Mediterranean coast (Jiménez et al., 2017; Horst Sterr et al., 2019). These seagrass species have high ecological value in marine environments as they provide shelter to sea animals, produce oxygen, and have seawater filtering properties (Campagne et al., 2015; Schenke & Müller, 2018; Orth et al., 2020). However, by the end of their lifespan, seagrass leaves detach and are transported by wind and water currents (Jiménez et al., 2017; Liu et al., 2019a). The detached leaves wash up on the shore where they contribute to the formation of beach wrack as banquettes or aegagropiles.

Seagrass wrack is considered a nuisance by many coastal communities (Davies et al., 2007) and is a substantial contributor of **greenhouse gas** emissions when left to decompose on the beach (Liu et al., 2019a). Local coastal authorities aim to avoid the disturbance on landscape and smell to keep the beach attractive for recreation and tourism (Davies et al., 2007). Yet, collecting and managing this waste stream have incurred in high costs and in further environmental impacts (Sterr et al., 2019; Mainardis et al., 2021). For instance, German seaside resorts have reported costs of up to €38 per meter of coastline for beach wrack collection (Mossbauer et al., 2012). Furthermore, the most common way of management in Europe of seagrass wrack is landfilling (Mainardis et al., 2021). Disposing seagrass in landfills is the least preferred practice in waste management (European Waste Framework Directive) and is an activity that can strongly contribute to global warming (Mainardis et al., 2021).

Considering the previous issues and in the context of Wageningen University & Research (WUR) vision for the Netherlands in 2120 (WUR, 2019), ArtEZ Future Makers is exploring the possibilities of using seagrass wrack found in European beaches for textile applications. Using this waste stream matches with European Union's circular economy goals; which aim to add value to a product or material even at the end of its life cycle, thus reducing waste to minimum (European Parliament, 2015). So, the valorisation of seagrass wrack provides an opportunity to improve an industry strongly responsible for environmental pressures such as resource use, land use, climate change and release of pollutants (European Environment Agency, 2021).

1.2 RESEARCH OBJECTIVE

The intention of this consultancy project is to collaborate with ArtEZ Future Makers to provide an academic perspective on the use of washed up seagrass as a sustainable resource in Europe. A previous ACT group investigated seagrass as a fibre and cellulose source for the commissioner, but it remained unclear which properties and functionalities could derive from it. Our participation aims to identify the properties and applications of two common seagrass species washed up on European coastlines, *Z. marina* and *P. oceanica*, and evaluate the environmental implications of its use. The consultancy project's objective can be reflected in the following research question and its sub-questions:

What are the qualities of washed up *Z. marina* and *P. oceanica* on European coastlines and the environmental benefits of using this waste stream?

1. What are the physical and chemical characteristics of washed up *Z. marina* and *P. oceanica*?

2. How do growing conditions and environmental factors influence the properties and quality of washed up *Z. marina* and *P. oceanica*?

3. Which applications derive from the physical and chemical characteristics of washed up *Z. marina* and *P. oceanica*?

4. What are the effects on the environment of using washed up seagrass as a resource?

2 METHODOLOGY

Literature review: The topics that will be discussed are the physical and chemical characteristics of the seagrass species, the possible applications and the effects of using washed up seagrass on the environment. These properties can change depending on growing conditions and environmental factors. The application studied will be traditional ones and novel ones. Environmental effects of seagrass after washing up that can be thought of are the function of the seagrass on the beach in preventing erosion, the emission of greenhouse gasses (CO_2, CH_4) during decomposition, and the current waste management (landfilling).

Expert consultation: To fill some knowledge gaps, various experts were consulted. These include: Michiel Bartels, a Dutch archaeologist in West Friesland, and Frans Segers, owner of the mattress company Lavital and Tiny van Teulingen-Molenaar, coordinator of the archive at the Historische Vereniging Wieringen.

3 STAKEHOLDER ANALYSIS

We have conducted a stakeholder analysis to map the different stakeholders who play a role in the use of washed up seagrass as a resource. Figure 1 represents a stakeholder matrix which includes all the stakeholders. The stakeholders of interest for our specific project are described below in the short-list and the remaining stakeholders are described in Appendix 1.

Short-list stakeholders:

- Authorities of EU beaches: This industry has a high power over the seagrass wrack collection, since the material is a nuisance to beach users and tourists. Moreover, the authorities of EU beaches face significant costs to remove the beach wrack and a local solution that increases the value of beach wrack might be interesting to them. Authorities of Køge Bay in Denmark, Rugen Island in Germany and Port-Cros Island in France are some of the few who have been affected by beaches with seagrass wrack (Chubarenko et al., 2021; Otero et al., 2018).

- ArtEZ Future Makers: This Centre of Expertise Future Makers has a relatively high power due to their cooperation with partners such as research centres, governments, and companies. Moreover, it has a very high interest in this project as they initialized this project and aim to make value chains in fashion and textiles more sustainable, which can potentially be realized with seagrass.

- Innovative designers: These designers have a high interest in seagrass because it could become a novel and sustainable application in their designs. However, their power is limited because they have limited influence on the market and seagrass wrack collection.

- Research institutes: Research institutes have the most knowledge on seagrass and therefore some power. Moreover, application of seagrass interests them because it can help the transition of industries towards a more fair, clean and sustainable future.

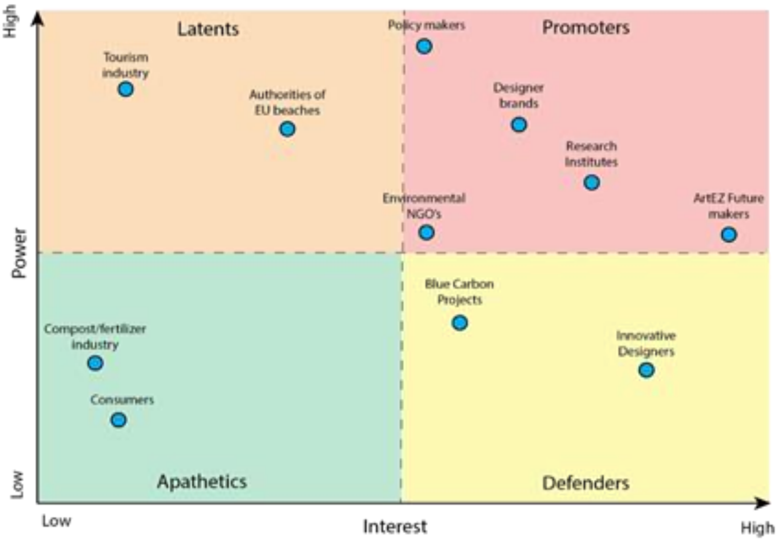

Figure 1 Stakeholder matrix of the use of washed up seagrass as a resource

4 SEAGRASS CHARACTERISTICS

Seagrasses are marine vascular flowering plants that have evolved from freshwater plants over three to four separate lineages (Borum et al., 2004). In total, there are around 60 species within 12 genera. Seagrass species can be found in shallow waters bordering all continents except antarctica (McKenzie et al., 2020). This large geographical distribution is facilitated by the large variation in shape and morphology that can occur within and between species (Les et al., 1997; Trevathan-Tackett et al., 2017). All seagrass species are flowering plants that have the ability to reproduce sexually. Here, pollen and the resulting seeds are spread by the water currents present at the seagrass meadows. However, these plants also have to ability to reproduce clonally, which can be more energy efficient, resulting in most new plant originating from clonal reproduction through extending rhizomes. Rhizomes refer to specialised organs that look like roots but are actually modified stems. From these stems, new plants can grow. In this manner a single plant can quickly colonize large surfaces with its clonal offspring, creating vast seagrass meadows. Detached rhizomes can also be carried away by the current and take root in a new region, where they can begin the formation of new meadows.

As mentioned before, this research will focus on the two common seagrass species washed up on European coastlines, *Z. marina* and *P. oceanica*. These species have different characteristics that can facilitate different uses. In this chapter, physical and chemical characteristics of both species will be discussed. First we will introduce the biological characteristics of both species (Chapter 4.1). Secondly, we will discuss the chemical composition and physical characteristics of the washed up seagrass (Chapter 4.2). Finally, the environmental factors affecting the aforementioned characteristics will be discussed (Chapter 4.3).

4.1 BIOLOGICAL PROPERTIES

Two species account for the majority of seagrass meadows in the waters surrounding the European continent: *Z. marina* and *P. oceanica*.

In the cold coastal waters of the Northern Atlantic Ocean and the Baltic Sea, two species of seagrass can be found: *Z. marina* and Zostera noltii. Out of these two species *Z. marina* accounts for the majority of washed up biomass, especially in the Baltic Sea (Borum et al., 2004), and will be the focus of our research on the Northern and Western European coastlines. In the warmer waters of the Mediterranean, both Zostera-species can be found in isolated patches but are generally outcompeted by two seagrass species indigenous to the region: Cymodocea nodosa and *P. oceanica*. Of these two species, *P. oceanica* is by far the most dominant species and is responsible for vast quantities of biomass washing up in the

Mediterranean. Although beach wrack is often composed of multiple species at once, Z. marina and P. oceanica generally make up most of the beach wrack in their respective regions and primarily determine the characteristics of this beach wrack.

4.1.1 *ZOSTERA MARINA*

Z. marina, also known as eelgrass, can be found around the globe in the cold waters of the Northern Atlantic and Pacific oceans. In Europe the species can be found in large meadows along the Atlantic and Baltic coasts (Figure 2). Z. marina can be found from Iceland and Northern Norway down to the Mediterranean, but is most abundant within the Baltic Sea, North Sea and the Atlantic coast along Northern Spain. This species grows at a depth of 10-15 meters and is predominantly subtidal and perennial, although intertidal, annual populations also occur. These intertidal populations generally have smaller, more flexible leaves than their subtidal siblings, although they still belong to the same species. (Oetjen & Reusch, 2007) In general, each shoot has 3-7 leaves, with a length of 30-60 cm and a width of 2-10 mm (Borum et al., 2004). The leaves have an average lifespan of 88 days (Borum et al., 2004), and the shoots grow terminal on a horizontal rhizome (Figure 3). *Z. marina* has small green male and female flowers partly hidden between the leaves. The flowering period is from early spring to fall, and they flower several times. Additionally, they shed their leaves 2 times a year (Bartels et al., 2016). The seed production is over several thousand seeds/m2/year (Borum et al., 2004).

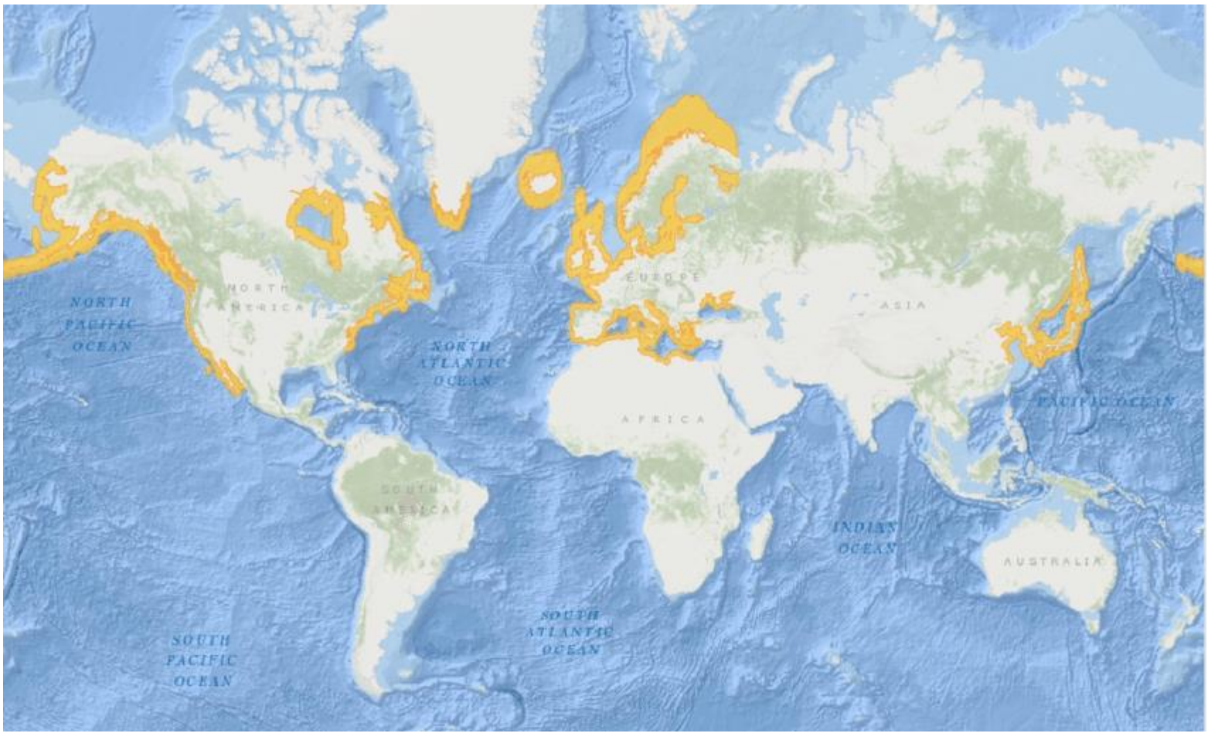

Figure 2 Geographical distribution of *Z. marina* (Gundersen et al., 2017)

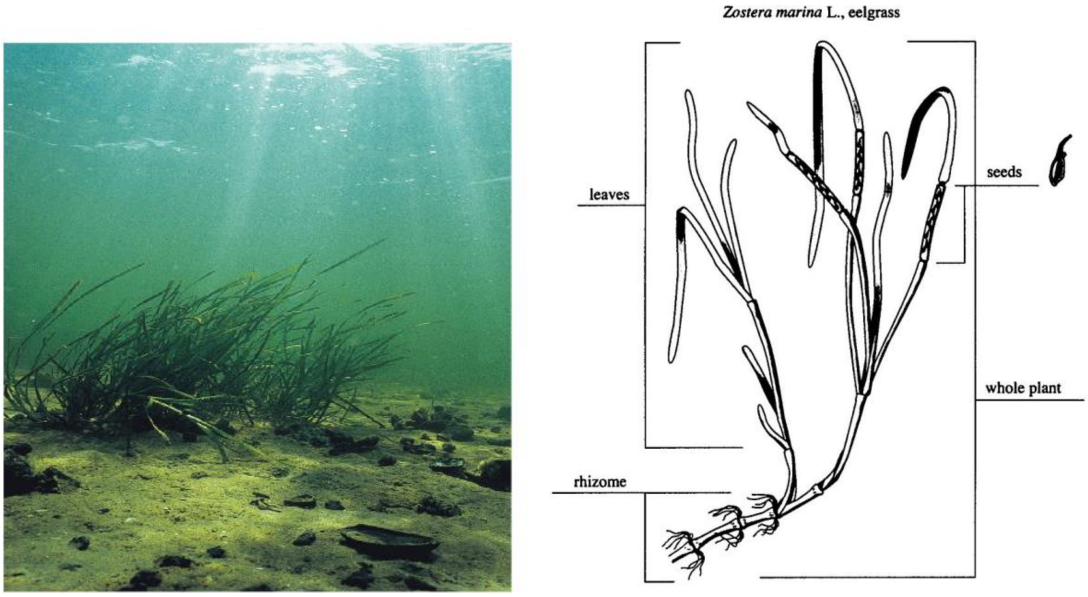

Figure 3 *Z. marina* (eelgrass). Picture of seagrass on the seafloor (left) (Borum et al., 2004) and schematical drawing of *Z. marina* (right) (adapted from (Wyllie-Echeverria et al., 2000))

4.1.2 *POSIDONIA OCEANICA*

P. oceanica is the most widespread higher plant in the Mediterranean Sea, but solely grows in the Mediterranean as well where it washes up on the beach (Figure 4). Here, the plants can grow at a depth of up to 50-60 meters, their leaves have a length of 20-40 cm and are denser and broader (5-12 mm) in comparison to *Z. marina*.

From the horizontal rhizomes many vertical rhizomes arise that are packed with dense hairs of old, degrading leaf sheets (Figure 5). The remains of these leaf sheets can aggregate into complex fibrous balls called “aegagropiles” or “Neptune balls”, which can be found alongside the leaf banquettes on many Mediterranean beaches (Lefebvre et al., 2021). The leaves have an average life span of 295 days (Borum et al., 2004) and mainly detach during autumn and winter (Otero et al., 2018). These detached leaves can wash up on the shore and form banquettes. *P. oceanica* rarely flowers (<1 flower/10m2/year) and reproduces vegetatively by branching of rhizomes (Figure 6) (Borum et al., 2004; C. Boudouresque et al., 2012). It was estimated that 2.5 - 4.5 million of hectares of the Mediterranean seafloor is covered by P. Oceanica (Diaz E & Marbá N, 2009).

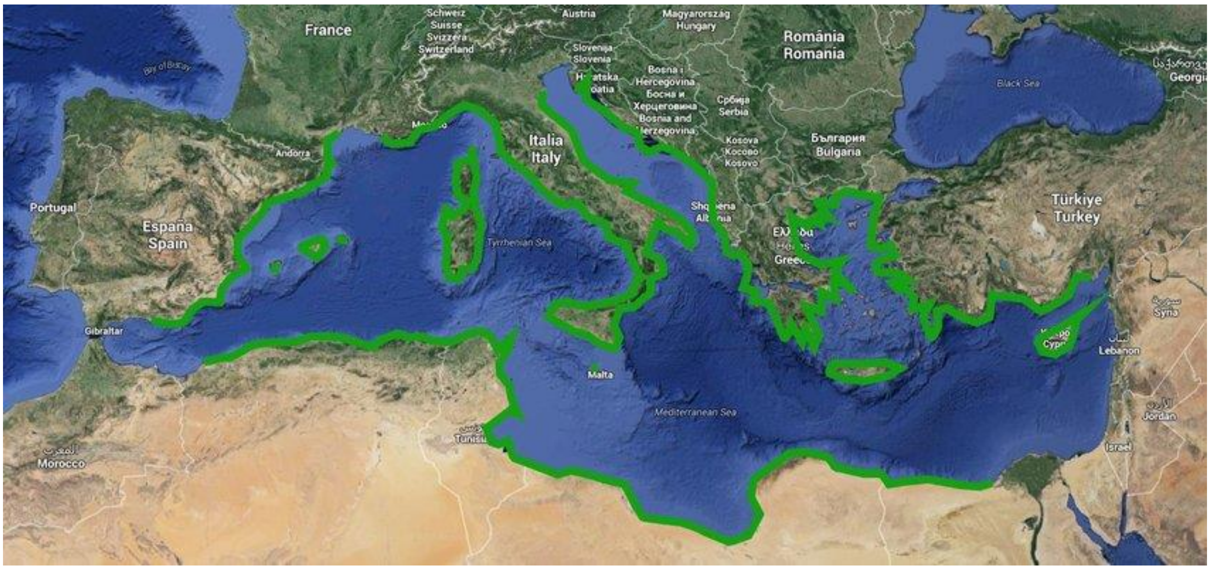

Figure 4 Geographical distribution of *P. oceanica* in the Mediterranean (Remy, 2016)

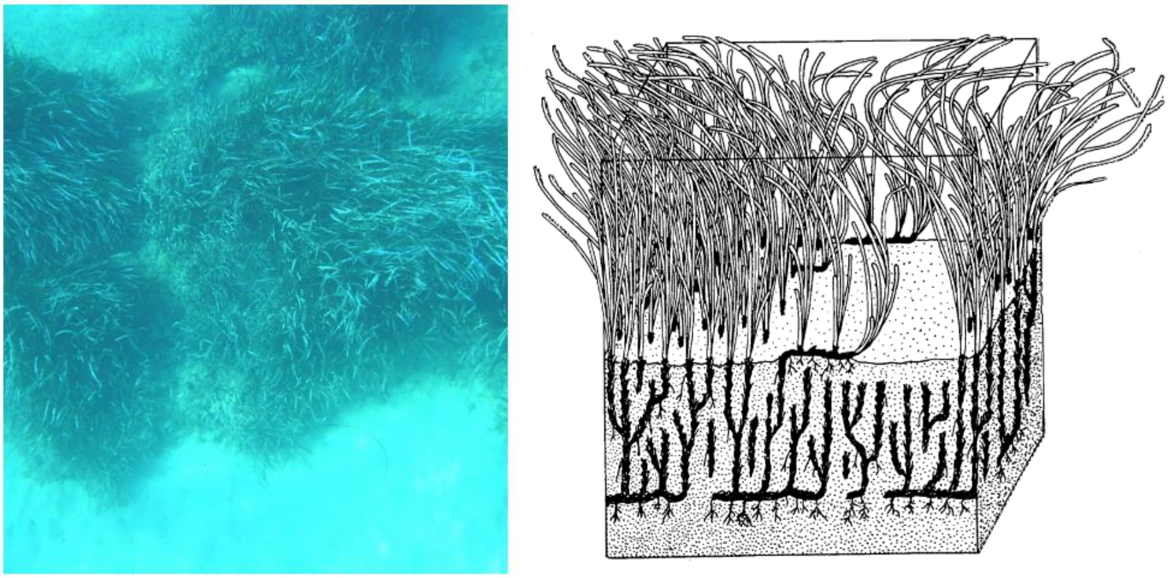
Figure 5 *P. oceanica* (Neptune grass). Picture of Neptune grass in the sea (left) (Borum et al., 2004) and schematical drawing (right) (Adapted from: (C. Boudouresque et al., 2012))

4.2 CHEMICAL & PHYSICAL PROPERTIES

4.2.1 CHEMICAL COMPOSITION

The chemical composition of seagrass consists of: (1) the elemental composition and (2) biochemical composition. The elemental composition gives insight in the number of chemical components that make up seagrass. This is, for instance, useful if you want to know the value of seagrass as organic fertilizer and/or compost. The nutritional composition gives insight in the abundance of the major nutrients in seagrass such as carbohydrates, proteins and lipids.

This can be useful for applications such as anaerobic digestion. The chemical composition of seagrass is variable and dependent on of seagrass species, seasonal variability, wrack 'age' and plant material type. Therefore, there is a difference in the chemical composition between P. oceanica leaves, P. oceanica balls (Neptune balls) and Z. marina leaves. Mission et al. found a moderate seasonal variability of about 10% change in seaweed wrack composition, which indicates no large changes to seagrass biomass over the seasons (as they are the main composites of beach wrack) (Baltic Sea Action Plan – HELCOM, n.d.-a). In this chapter we only take into account the species and plant material. The effect of time on the wrack will be further discussed in Chapter 4.3.

There are few studies on the elemental composition of seagrass wrack and most studies look at the elemental composition of digested / composted seagrass. This is understandable since the elemental composition of seagrass is mainly important for applications such as compost, organic fertilizer, **biochar** or **anaerobic digestion** (AN).

4.2.1.1 ELEMENTAL COMPOSITION

Table 1 shows that washed up Z. marina and P. oceanica.(Neptune balls + leaves) contain essential nutrients such as organic Carbon (C), Nitrogen (N) and Phosphorus (P). The main difference between Z. marina and P. oceanica is related to the C/N ratio, which is significantly higher for P. oceanica leaves (49.5) in comparison Z. marina (23.1) and Neptune balls (22.4). The C/N ratio of biomass is related to the microbial activity during decomposition reactions such as AN or composting. A C/N ratio between 15-30 gives an optimal microbial activity during decomposition and indicates that Z. marina wrack and Neptune balls are better suited for decomposition than P. oceanica leaves. In decomposition reactions with higher C/N ratios, in case of P. oceanica leaves, there won't be enough nitrogen to sustain microbial growth (Ecomare, n.d.). However, Sterr et al. argued that the assumption for fast decomposition of Z. marina did not correspond to observations made along the Baltic coast (H Sterr et al., n.d.). Instead, according to them, the decomposition rate also depends on the complexity of the molecules in which nitrogen and carbon are present.

Table 1 Elemental composition of washed up *P. oceanica* (leaves and balls) and *Z. marina* (DM: Dry matter)

Element composition	*P. oceanica (balls)*	*P. oceanica (leaves)*	*Z. marina (leaves)*	Unit	Reference
C	46 - 56	37.8 – 46.5	37 - 39	% DM	(Cocozza et al., 2011b; Fourqurean et al., 2007; Ramzi Khiari et al., 2011; Mateo et al., 2003; Strandressource, 2019)
N	0.3 - 2.5	0.6 – 1.63	1.7 – 2.1	% DM	(Cocozza et al., 2011b; Ramzi Khiari et al., 2011; Mateo et al., 2003; Strandressource, 2019)
O	36.8	N.A.	52.6	% DM	(Ramzi Khiari et al., 2011)
H	N.A.	N.A.	6.4	% DM	(Strandressource, 2019)
P	N.A.	0.1 - 0.02	0.15	% DM	(Mateo et al., 2003)(Strandressource, 2019)
C/N	22.4	28.4 - 85	23.1	-	(Cocozza et al., 2011b; Mateo et al., 2003; Strandressource, 2019)
C/H	N.A.	N.A.	5.8	-	(Strandressource, 2019)

Z. marina and P. oceanica have a similar salt content between 0.5 - 2% which contributes to the flame retardant properties of seagrass (Insulating Materials: Principles, Materials, Applications - Margit Pfundstein, Roland Gellert, Martin Spitzner, Alexander Rudolphi - Google Boeken, n.d.). The ash content, shown in Table 2, varies between species and is also dependent on the environmental factors. For instance, seagrass can accumulate more undesirable heavy elements (e.g. copper (Cu), lead (Pb) and cadmium (Cd)) when the meadow is close to an urban center. P. oceanica has a higher ash content than Z. marina which gives makes it more suitable for nutrient rich compost or biochar. Moreover, elements such as boron (B) and iodine (I) in the ash have antimicrobial properties, which prevents molding of seagrass when its used in applications such as fillings or insulation (H Sterr et al., n.d.).

Table 2 Ash composition of washed up *P. oceanica* (leaves and balls) and *Z. marina* (DM:dry matter; N.A.: not available).

Ash composition	*P. oceanica (balls)*	*P. oceanica (leaves)*	*Z. marina (leaves)*	Unit	Reference
Total ash	12 - 13	17 - 19	10.47	% D.M	(Cocozza et al., 2011b; Misson et al., 2020)
Ca	9.1	3.9	1.9	%	(R. Khiari et al., 2010; Shams El Din & El-Sherif, 2013)
Mg	3.9	N.A.	0.83	%	(R. Khiari et al., 2010)
K	2	0.5	0.49	%	(R. Khiari et al., 2010; Shams El Din & El-Sherif, 2013)
Na	2.5	2.8	3.3	%	(R. Khiari et al., 2010; Shams El Din & El-Sherif, 2013)
Si	17.7	N.A.	N.A.	%	(Cocozza et al., 2011b)
B	2.32	3.04	N.A.	%	(Cocozza et al., 2011b)

4.2.1.2 BIOCHEMICAL COMPOSITION

Table 3 shows that Z. marina wrack contains a significant fraction of lignocellulosic material (42.5 % D.M.) that consists of cellulose, hemicellulose and lignin. This material (especially cellulose and lignin) degrades slower than soluble substances, such as other carbohydrates (starch) and proteins. P. oceanica has even higher fractions of lignocellulosic material than z. marina of up to 86% and 91.6% for leaves and Neptune balls respectively (R. Khiari et al., 2010; Misson et al., 2020). The differences between the lignocellulosic fractions of the different materials is mostly due to the difference in lignin content. Z. marina has a significantly lower (5%) lignin content than P. oceanica (29.8% and 27% for Neptune balls and leaves respectively). A high lignocellulosic content boosts humus formation in compost but can also decrease valorisation by anaerobic digestion due to reduced access for microorganisms (Misson et al., 2021). Furthermore, a high lignin content in biomass envisages uses in papermaking applications or application in fibre-reinforced composite materials (R. Khiari et al., 2010; Ramzi Khiari et al., 2011; Scaffaro et al., 2018).

Lastly, seagrass 'wrack' is often contaminated with algae, other marine plants and sand. Therefore, there is a large variability in the chemical composition data. To obtain accurate information on seagrass (wrack) used by ArtEZ Future Makers, laboratory research has to be conducted.

Table 3 Biochemical composition of washed up P. oceanica (leaves and balls) and Z. marina (DM: dry matter, FM: fresh matter and N.A.: Not available).

Biochemical components	*P. oceanica (balls)*	*P. oceanica wrack (leaves)*	*Z. marina wrack (leaves)*	Unit	Reference
Moisture	N.A.	N.A.	82.6	% FM	(Misson et al., 2020)
Salt	0.5 - 2	N.A.	1.97	% DM	(*Eigenschaften*, n.d.; Misson et al., 2020)
Carbohydrates	N.A.	N.A.	62.24	% DM	(Misson et al., 2020)
Proteins	N.A.	N.A.	11	% DM	(Misson et al., 2020)
Lipids	N.A.	N.A.	1.42	% DM	(Milchakova et al., 2014)
Cellulose	40	38	24.1	% DM	(R. Khiari et al., 2010; Misson et al., 2020)
Hemicellulose	22	21	16	% DM	(R. Khiari et al., 2010; Misson et al., 2020)
Lignin	29.8	27	2.4 - 5	% DM	(R. Khiari et al., 2010; Misson et al., 2020)

4.2.2 FIBRE COMPOSITION

Natural fibres attract progressively more interest for polymer reinforcement application as sustainable biodegradable alternative to fossil derived polymers. Recent studies have shown that plant fibres such as hemp, flax and jute are a promising alternative for e-glass fibres in the automotive industry (Sanjay et al., 2016). However, all these fibres are derived from terrestrial plants, while marine plant fibres also have considerable potential. Seagrass is one of the only marine plants that contains lignocellulosic structures, because of their terrestrial origin (Trevathan-Tackett et al., 2017). This is important since lignocellulose gives strength to the fibres, making them suitable for polymer reinforcement applications. Both P. oceanica and Z. marina have recently gained some attention as a possible fibre source. There are few studies on individual fibres since most studies instead measure the strength and stiffness of a seagrass reinforced compound.

4.2.2.1 *Z. MARINA* FIBRES

In Z. marina, fibres are present in bundles of 6 to 12 fibres on the surface side of the leaves as shown in Figure 6 (Davies et al., 2007). Structurally these fibres are different than most fibres of terrestrial plants (Table 4A) as they have a smaller diameter (4.6 µm) and contain less cellulose, but more significantly more hemicellulose than other terrestrial fibre plants such as flax (17.8 µm, 82% cellulose, 7% hemicellulose), hemp (10-50 µm, 78% cellulose, 5.5% hemicellulose) and jute (25 – 200 µm, 64.4% cellulose, 12% hemicellulose) (Davies et al., 2007). The mechanical properties seen in Table 4B are promising but inferior to e-glass fibres (76 GPa, 1400-3500 MPa) (Davies et al., 2007) or polyester (13 GPa, 1260 MPa) (Lechat et al., 2006).

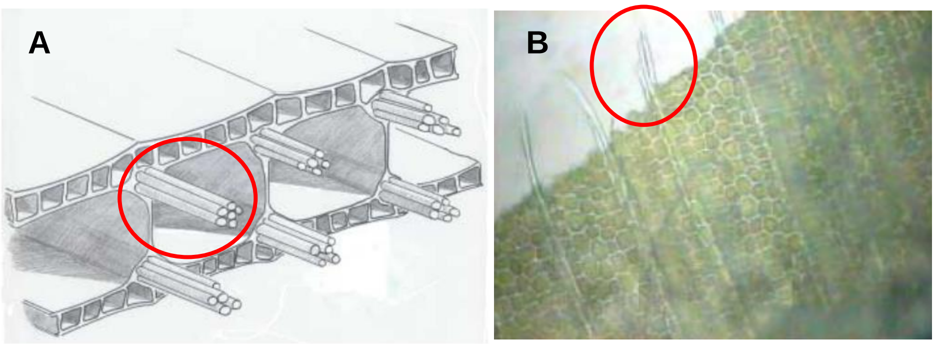

Figure 6 Sketch (A) and micrograph (B) and of a Z. marina grass blade with circles showing position of the fibre bundles. (Obtained from (Davies et al., 2007).

Table 4 Fiber composition (A) and mechanical properties (B) of *Z. marina*. Data is obtained from (Davies et al., 2007)**. <u>Tensile modulus</u> gives the stiffness of the material (how much does a material deform under a particular load). Tensile <u>strength</u> gives the stress when the fibre breaks.**

Fibre composition	*Z. marina (leave fibres)*	Unit
Holocellulose	85	%
Cellulose	57	%
Hemicellulose	28	%
Pectin	10	%
Lignin	5	%

Fibre mechanical properties	*Z. marina (leave fibres)*	Unit
Diameter	4.6	µm
Tensile modulus	19.8	GPa
Tensile strength	573	MPa
Failure strain	3.4	%

4.2.2.2 *P. OCEANICA* FIBRES

In contrast to *Z. marina*, there is no available information on the composition and mechanical properties of individual *P. oceanica* (leaves and neptune ball) fibres. However, both Neptune balls and leaves have been successfully used to reinforce materials. Table 5 gives an overview of improved mechanical properties of some seagrass reinforced materials, that can be used as inspiration for ArtEZ Future Makers. In this table two mechanical properties are listed: (1) Tensile strength and (2) tensile modulus. Tensile strength is the maximum of stress that a material can endure before in breaks. Tensile modulus evaluates the stiffness of a material which is the relation between material deformation and the required power. These two parameters give insight in the tensile properties of a material which the mechanical properties are partly constituted of.

Table 5 Mechanical properties of *P. oceanica* reinforced composites (Weight percentage: %wt). Tensile modulus gives the stiffness of the material (how much does a material deform under a particular load). Tensile strength gives the stress when the fibre breaks

Filler	*Filler 2*	*Matrix*	**Loading**	***Tensile strength (MPa)***	**Tensile modulus (MPa)**	**Ref.**
~~Neptune balls~~	X	BIOPLAST GF 106	0 wt%	17.5	67.52	(Ramzi Khiari et al., 2011)
Neptune balls	X	BIOPLAST GF 106	30 wt%	18.2	180.5	(Ramzi Khiari et al., 2011)
P. oceanica leaves (PO)	Wood (W)	Methylene diisocyanate (MDI)	0 (PO) /100 (W) 30 wt% MDI	5.93	1053	(Maciá et al., 2016)
P. oceanica leaves (PO)	Wood (W)	Methylene diisocyanate (MDI)	75 (PO) / 25 (W) 30 wt% MDI	4.46	1241	(Maciá et al., 2016)
~~*P. oceanica* leaves (PO)~~	X	Polylactic acid (PLA)	0 wt%	51.1	1891	(Scaffaro et al., 2018)
~~*P. oceanica* leaves (PO)~~	X	Polylactic acid (PLA)	20 wt%	39.2	2219	(Scaffaro et al., 2018)
~~Neptune balls~~	X	Polhydroxyalkanoate (PHA)	0 wt%	24.8	1240	(Seggiani et al., 2017)
Neptune balls	X	Polhydroxyalkanoate (PHA)	20 wt%	22.78	1820	(Seggiani et al., 2017)
~~Neptune balls~~	X	Polyethylene (PE)	0 %wt	36.64	1300	(Puglia et al., 2014)
Neptune balls	X	Polyethylene (PE)	20 %wt	38.71	1540	(Puglia et al., 2014)

Table 5 shows that addition of P. oceanica filler material generally increases the tensile modules by making the composite material stiffer. Hereby, it can bear more load and thus will undergo less deformation (Ramzi Khiari et al., 2011; Puglia et al., 2014; Scaffaro et al., 2018; Seggiani et al., 2017). However, in some cases the tensile strength decreases in comparison upon addition of P. oceanica filler material, which can explained by inadequate adhesion between the matrix and filler. A common problem with natural lignocellulosic fibres is their hydrophilic character that is incompatible with hydrophobic matrices such as PLA. Pre-treatment of the natural fibres can increase the compatibility between the fibres and matrices, therefore enhancing the overall mechanical properties (Bledzki & Gassan, 1999).

Furthermore, Scaffaro et al. highlighted that tensile properties of the PLA composite were influenced by the length/size of P. oceanica filler material (Scaffaro et al., 2018). Larger particles of 300 µm showed less tensile strength (37.5 MPa) and modulus (2125 MPa) than smaller 150 µm particles (Tensile strength (39.2 MPa) and modulus (2219 MPa)). Therefore, length/size should be taken into account when working with P. oceanica fibres. Overall, the mechanical properties of P. oceanica are promising as a filler in composites.

4.2.2.3 FIBERS AS AN INSULATION MATERIAL

Seagrasses have a long history as insulation material due to their excellent insulation properties. Furthermore, dried seagrass is naturally mold and fire resistance and doesn't require treatment with hazardous substances. Table 6 gives an overview of the known thermal conductivity and specific heat capacity of *Z. marina* and *P. oceanica*. Thermal conductivity describes the ability of a material to conduct heat while heat capacity describes the amount of energy needed to cause an increase in temperature of a material. A low thermal conductivity is therefore important to keep heat contained in a building during the winter while a high specific heat capacity keeps the warmth outside during the summer.

Table 6 Thermal conductivities and specific heat capacities of *P. oceanica* and *Z. marina* (Pallets: tightly packed fibres/leaves).

Species	Material type	Binding agent	Density (kg/m^3)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Specific heat capacity ($J\ kg^{-1}\ K^{-1}$)	Ref.
P.oceanica (leaves)	Pallet	No	185	0.044	N.A.	(Carmona et al., 2018)
P.oceanica (balls)	Pallet	Yes	175	0.037	N.A.	(Greiner, n.d.)
-	Loose fibres	No	95	0.042	N.A.	(Greiner, n.d.)
-	Loose fibres	No	65 - 75	0.039	2599	(*Eigenschaften*, n.d.)
Z. marina	Loose leaves	No	70 - 80	0.045	2000	(*Seegras Dämmstoff von Der Ostsee*, n.d.)

P. oceanica and Z. marina have comparable thermal conductivities and specific heat capacities that are comparable to conventional insulation materials such as expanded polystyrene (23 kg/m3 ,0.036 W m-1 K-1, 1460 J kg-1 K-1) (Lakatos & Kalmár, 2012). Pallets seem to have slight lower thermal conductivity values than loose leaves and fibres, which can be attributed to a higher material density. Therefore, to achieve maximum thermal insulation, the weight of the seagrass pallets would be three to four times higher than conventional insulations, such as expanded polystyrene. However, the extra weight can easily be supported by residence buildings (Carmona et al., 2018). Furthermore, it is claimed that P. oceanica (Neptune) balls give the best heat protection in the summer due to a high specific heat capacity. Lastly, installing seagrass is still relatively expensive (0.8 €/kg) but it can be easily discarded at the end of the products' life-cycle (composting) (Seegras Dämmstoff von Der Ostsee, n.d.).

4.2.3 SECONDARY METABOLITES

Secondary metabolites are organic compounds produced by plants that are not directly involved in a plant's development, reproduction and growth. Instead these compounds are produced to increase survivability and/or fertility to gain a selective advantage over other plants. The most common secondary metabolites in plants are **terpenoids**, alkaloids and phenolic compounds. These compounds often play a role in the plant's defense against herbivory or other species such as bacteria and fungi. Humans use secondary metabolites as medicines (antibiotics), pigments (carotenoids) flavorings (flavonoids), recreational drugs (cocaine) and more.

Seagrasses contain many secondary metabolites but only few are interesting for human use (Heglmeier & Zidorn, 2010). The amount of the secondary metabolites present in the leaves (Figure 7) is variable and depends on the age and environmental conditions such as temperature (Ravn et al., 2012). Moreover, studies show discrepancies in the secondary metabolite diversity and concentrations within the same species, which indicates that the identification of secondary metabolites is also highly depended on the extraction method (Grignon-Dubois & Rezzonico, 2015). Therefore, instead of the concentration, only the availability of the most important secondary metabolites will be shown in Table 7. This table gives an overview of the most important secondary metabolites (most abundant) present in *P. oceanica* and *Z. marina* and includes the natural functions and potential human uses. The presence of secondary metabolites, together with the high mineral concentrations (Table 7), ensure that seagrass is (mildly) antimicrobial (fungi and bacteria). This prevents mold formation when used as insulation or filling (Strandressource, 2019).

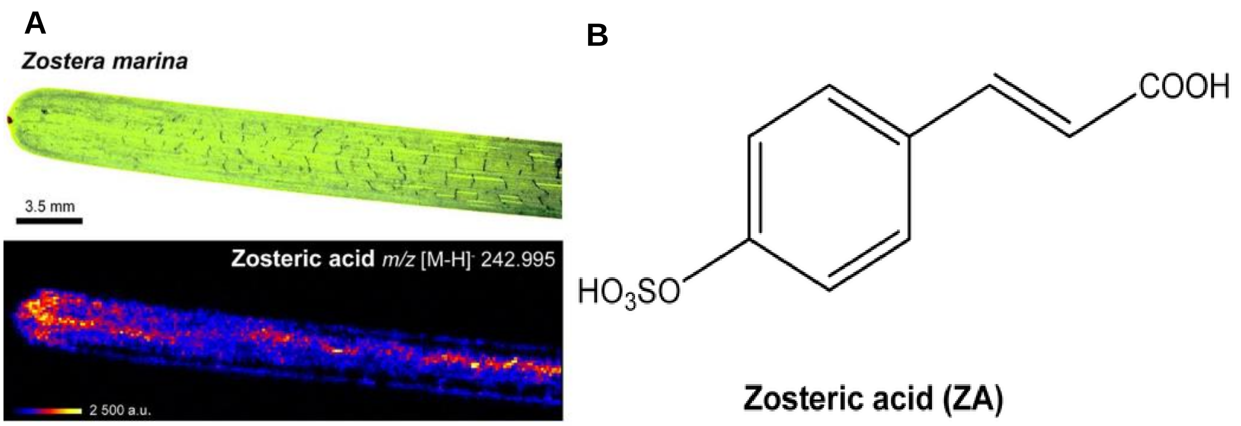

Figure 7 *Z. marina* leave with the location of zosteric acid (A) and the molecular structure of zosteric acid (B) (Obtained from (Papazian et al., 2019)

Table 7 Secondary metabolites of *P. oceanica* and *Z. marina* with the plant function and possible human functions.

Z. marina				
Secondary metabolite	**Type**	**Plant functions**	**Human functions**	**Ref.**
Zosteric acid	Phenolic	Anti-adhesion (versus microorganisms)	Surgical adhesion drug (against scar tissue formation) Antioxidant Anti-inflammatory New antifouling compound	(Achamlale et al., 2009; Taokaew et al., 2019; Xu et al., 2020)
Chicoric acid	Phenolic	Antimicrobial Tissue repairing	Anti-inflammatory Antioxidant Antivirus	(Grignon-Dubois & Rezzonico, 2015; PengYe et al., 2019)
Rosmarinic acid	Phenolic	Antimicrobial Anti-grazing	(Potentially) Antioxidant	(Choi et al., 2009; Ravn et al., 2012)
P. oceanica				
Chidoric acid	Phenolic	Antimicrobial Tissue repairing	Anti-inflammatory Antioxidant Antivirus	(Grignon-Dubois & Rezzonico, 2015; PengYe et al., 2019)
Caftaric acid (esterified caffeic acid)	Phenolic	N.A.	(Potentially) Antioxidant (Potentially) Anti-inflammatory (Potentially) Anti-diabetic (Potentially) Antimutagenic	(Mohamed & Koriem, n.d.)

4.3 QUALITY OF WASHED UP SEAGRASS

The chemical and physical characteristics of washed up seagrass can differ tremendously based on the environment in which the seagrass has grown (growing conditions) or to which it is exposed once it has washed up (environmental conditions). Knowledge on the growing conditions could help determine the best location to gather seagrass from, based on the properties required for specific purposes. A better understanding of the environmental effects influencing the characteristics of washed up seagrass can help determine the ideal time of collection for a specific use.

4.3.1 GROWING CONDITIONS

The physical and chemical characteristics of individual seagrass plants can change depending on their environment. The environment can exert influence on the plant characteristics through a complex interplay of biotic and abiotic factors (Heglmeier & Zidorn, 2010). Biotic factors encompass the effects of living organisms on the plant (e.g. grazing, **epiphytes** and competition between organisms). Abiotic factors on the other hand, describe the effect of non-living components on the plant (e.g. temperature, nutrient concentration and salinity). These factors are constantly influenced by each other and in a complex interplay influence plant characteristics. In this chapter the most important forces shaping seagrass are listed and their relevance is explained.

Temperature is an important abiotic factor that is known to influence the physical and chemical characteristics of Z. marina. Due to the widespread distribution of Z. marina, it can be found in different climates across Europe. In warmer climates, the leaves become significantly shorter, wider and have a lower fibre content (Paul & de los Santos, 2019). Increased temperatures can also lead to higher concentrations of amino acids and soluble sugars in the leaves. Additionally it can lead to a decrease in cellulose, one of the main components of fibres (Touchette & Burkholder, 2002).

A second abiotic factor that is specific for marine plants, is the hydrodynamic force. Z. marina can grow in intertidal regions but is mostly found in subtidal regions of up to 15 meters deep. In this range, water currents can differ significantly which has an effect on the morphology, which inherently leads to tougher plants. In more shallow waters, the leaves of Z. marina generally become shorter, more narrow and more flexible (Paul & de los Santos, 2019; van Duren & van Katwijk, 2015).

Another factor influencing growth is the amount of light that can reach the plants. This phenomenom is called light penetration and is influenced by e.g. the clearness of the water and the depth on which the plants grow. In turn, the clearness of the water is influenced by the nutrient concentration. Higher nutrient concentrations can cause an increase in free-swimming phytoplankton and algae, but also of epiphytes which decreases the clearness of the water (Pazzaglia et al., 2020). When the water is more clear or when plants grow less deep, more light can reach the plants which leads to higher plant density. On the other hand, lower light intensities can lead to a decrease of phenolic acids in Z. marina, rendering the plant more susceptible to infections (Vergeer & Develi, 1997); and to an increase in the amount of chlorophyll to optimally use remaining light reaching the plant (Cabello-Pasini, Muniz-Salazar, & Ward, 2004).

4.3.2 ENVIRONMENTAL FACTORS

As soon as seagrass tissue detaches from the plant it is prone to decomposition. This decomposition already starts in the sea and continues when seagrass washes up on the shore. Decomposition is carried out by many microorganisms that feed on the organic material. The decomposition rate is therefore mainly determined by how optimal the growing conditions are for the decomposers present in the beach wrack. Optimal growing conditions are determined by the moisture content and the availability of nutrients. Seagrass wrack that accumulates near the water's edge retains more moisture than beach wrack that has been moved (by nature or humans) further unto the beach (Liu et al., 2019b). This increased moisture content facilitates leaching of soluble compounds from the seagrass wrack that subsequently enhances the growth of decomposers(Liu et al., 2019b). Contamination of the beach wrack with external nutrient sources can occur, especially close to human populations. This increase in nutrients can boost bacterial colonization of the seagrass in a process called "microbial priming" and increase degradation of the biomass already before it washes up on shore (Trevathan-Tackett et al., 2017). It was also found that higher amounts of chemical deterrents in the leaves (a.o. phenolic acids) can slow down the decomposition by inhibiting the growth of microbial decomposers (Apostolaki et al., 2009). Nonetheless, decompositon of *Z. marina* can already cause a loss of dry weight biomass of 9% within the first two weeks (Vähätalo & Søndergaard, 2002). The decomposition is generally higher with higher temperatures (Trevathan-Tackett et al., 2017). Quick removal of seagrass could therefore significantly increase the amount of biomass that can be harvested. Decomposition of lignocellulosic biomass happens at a significantly slower rate and the chemical an physical properties of the fibers in the beach wrack (Trevathan-Tackett et al., 2017), do not change significanlty between different beach wracks on a single beach (Cocozza et al., 2011a). What does change significantly between seagrasswrack on the beach is the amount of sand, with seagrass wrack on the backshore that is further towards the dune generally containing more sand with larger grains than beach wrack on the foreshore (Simeone & De Falco, 2012).

5 POSSIBLE APPLICATIONS

Historically, seagrass has been used in many communities worldwide, including the Netherlands, France, Canada, Egypt, Italy and Mexico. The unique properties of these plant species have opened the possibilities to varied applications. In the following sections, a list of different applications will be introduced and explained based on the properties discussed in Chapter 4. Additionally, complementary data was obtained by consulting three experts: Michiel Bartels, a Dutch archaeologist in West Friesland, and Frans Segers, owner of the mattress company Lavital and Tiny van Teulingen-Molenaar, coordinator of the archive at the Historische Vereniging Wieringen . Some of the following practices date back to centuries ago, while others are novel and recently researched uses of this marine plant.

5.1 COMPOST/FERTILIZER

Traditionally, seagrass has been used to improve agricultural soil in France, the Mediterranean coast, and Mexico (C. Boudouresque et al., 2012; Riosmena & López, n.d.). In France and in the Mediterranean, farmers would burn or bury *P. oceanica* over the cropland to aerate over-compacted soil or maintain a rate of dampness in the surface soil (C. Boudouresque et al., 2012). While in Mexico, Seris, an indigenous group located in the State of Sonora, would use *Z. marina* as fertilizer (Riosmena & López, n.d.).

Nowadays, the use of seagrass for improving agricultural land has been identified in Germany and Spain (C. Boudouresque et al., 2012; Chubarenko et al., 2021). The municipality of Bad Doberan composts biomass found on the beach together with fresh terrestrial organic waste (Chubarenko et al., 2021). An important consideration is that sand content needs to be lowered to 30% for *Z. marina* to be successfully co-composted (Chubarenko et al., 2021). On the other hand, the municipality of Denya, with the help of European funding, worked on the design of a compost facility. They found that using *P. oceanica* together with other plants in the ratio of 1:3 resulted in a compost with good agronomical features due to its richness in **oligoelements** (C. Boudouresque et al., 2012). Sterr et al. (2019) reported that seagrass has a higher content of nutrients such as nitrogen, carbon, calcium, and manganese in comparison to organic waste compost.

Additionally, it was found that compost from *P. oceanica* can have a positive effect on soils in the following ways: decreases bulk density, increases porosity, increases ability to form more stable aggregates, reduces erosive phenomena, improves water holding capacity and conductivity, increases supply and availability of nutrients and favours the presence of microorganisms beneficial to plant development (Guido et al., 2013). Although, for soils to properly benefit from seagrass as a compost, it is important to verify the quality of the seagrass leaves. Heavy metals and/or pollutants found in seawater can be traced back in washed up seagrass leaves. Thus, if used as compost, these metals and pollutants can be transferred to the agricultural land, which can be detrimental to soil life and plant health (Horst Sterr et al., 2019).

5.2 FOOD & FEED

Seagrass leaves, fruits, and seeds have been used as food for people and livestock in Europe and Mexico (C. Boudouresque et al., 2012; Riosmena & López, n.d.). In Europe, the fruits of *P. oceanica* that were found on the beach were eaten by cattle, pigs, and even humans in times of famine (C. Boudouresque et al., 2012). While in Mexico, the indigenous group Seris, used to harvest *Z. marina* to eat (Riosmena & López, n.d.). Worldwide, the Seris have been the only community that has relied on seagrass for nutrition. As part of their traditional culture, each spring they harvested the ripe fruits of the plant. Nowadays, the community relies less and less on seagrass for food as they have integrated to national economic activities (Hernández, 2006).

In more recent practices, there have been some studies in Italy and Spain to understand the nutritional value of seagrass. In Italy, it was shown that adding powdered leaves of *P. oceanica* in the feed of hens improved the laying rate and egg weight (C. Boudouresque et al., 2012). Freshly-picked *P. oceanica* leaves have been compared with the nutritive value of hay and alfalfa (C. Boudouresque et al., 2012). In Spain, the chef Ángel León with his restaurant Aponiente is researching the use of *Z. marina* as a sustainable grain (Aponiente, n.d.). For the study, the team of Aponiente cultivated 3000 m^2 in Bahía de Cádiz and obtained the following key insights: yield estimates of 5-7 ton/ha in wild setting, no need of pesticides, no need of fertilizers and no irrigation, just the circulation of seawater and the seeds have excellent nutritional characteristics (Aponiente, n.d.).

5.3 BUILDING MATERIAL

Seagrass has been found in housings as roof covering, adobes (earthen housing), thermal and acoustic insulation (Borum et al., 2004; C. Boudouresque et al., 2012; Otero et al., 2018). In the early 20th century, coastal communities in Spain and North Africa such as Egypt, Libya, Tunisia used *P. oceanica* for building roofs (Borum et al., 2004; C. Boudouresque et al., 2012). Similarly, *Z. marina* was used in Denmark and within the Mexican indigenous community Seris as a material for roofs (Riosmena & López, n.d.; Visit Nordylland, n.d.). In some cases, seagrass was the substitute of other scarce building materials, such as straw (Borum et al., 2004). Although, it is believed it was also used due to its qualities for thermal insulation in France and in the Netherlands (C. Boudouresque et al., 2012)(Comment of Tiny van

Teulingen-Molenaar). For instance, a classical roof of barn in Corsica, France included a coating of *P. oceanica* (C. Boudouresque et al., 2012).

In the late 1800's, two companies in the South East of Canada started manufacturing commercial insulation quilts made of *Z. marina* (Wyllie-echeverria & Cox, 1999). Samuel Cabot Inc and Guildfords Limited produced insulation quilts by stitching leaves of different thicknesses between layers of heavy Kraft paper or asbestos (Wyllie-echeverria & Cox, 1999). Besides heat insulating properties, the companies advertised these quilts with low heat conductivity, acoustic dampening, low weight per volume, easy installation, flexible, fire-resistant, non-decaying, and of low cost (Wyllie-echeverria & Cox, 1999). The collection of the seagrass leaves was mostly done by locals in Yarmouth town. It was a seasonal activity, from July to October, that required little material investment. Farmers, fishers, and other craftsmen could participate with equipment they already owned (Wyllie-echeverria & Cox, 1999). Seagrass that washed up on the beach, or floating in nearby sea water, was gathered, and afterwards spread in the recent mowed hay fields to dry. Leaves were turned until they were completely dry and were then stored in sheds. For easier storage and transportation, seagrass leaves were pressed with hay balers (Wyllie-echeverria & Cox, 1999). For years, seagrass collection was an important economic activity for locals in Yarmouth. Unfortunately, both companies stopped production, one in 1940 and the other in 1960. It is believed these quilts were discontinued as fibre glass and other synthetic materials appeared in the market and as diseases decreased *Z. marina* population in Atlantic waters (Wyllie-echeverria & Cox, 1999). Similar forms of processing have been documented in the Netherlands (Bartels et al., 2016).

Nowadays, houses with *Z. marina* roofs can be found on the Island of Læsø in Denmark (Visit Nordylland, n.d.). These are over 300 years old and exhibit the durability of the material. A more contemporary approach to the use of seagrass in architecture can be seen in the Modern Seaweed House by Vandkusten Architects. The architecture firm restored a 150-year-old house on the Island of Læsø, but conserved the traditional concept materials, such as seagrass. *Z. marina* was incorporated as façade cladding and insulation, as its insulation value is close to mineral wool's (Vandkunsten Architects, n.d.).

At the moment, there is a German company called NeptuGmbH that sells insulation made from Neptune balls of *P. oceanica*. Neptune balls from the Mediterranean are collected and can be used in the building industry without any chemical. NeptuTherm is the branded product of NeptuGmbH and has a good insulating effect, mould resistance, low deterioration, is **hydroscopic** and has the possibility to compost by the end of its life cycle (see technical properties in Chapter 4.2) (Eigenschaften, n.d.).

5.4 DIKES

Since the 16th century, leaves from *Z. marina* were used to build dikes all around the Netherlands (Bartels et al., 2016; Borum et al., 2004); for example the West-Friese Omringdijk. Bartels et al. (2016) identified three methods in which seagrass was obtained by the Dutch: mowing, collecting the floating leaves in the sea or collecting the washed up seagrass on the beach. Mowing was typically done in June or July, but was very intensive work. Another possibility was the collection of the floating leaves. This activity started in June and continued until September. Locals would use ships and a good knowledge of the wind and water currents to guarantee the collection of a high volume of seagrass in little time. The alternative was to pick up the seagrass found on the beach (Bartels et al., 2016).

After collection, locals wanted to decrease the salt content and then let them dry to avoid unwanted decomposition. Therefore, the seagrass leaves would be spread out for 2 days over the dikes while held by hooks and ropes, so they wouldn't fly away with the wind (Bartels et al., 2016). Or, if the weather was not ideal, leaves would be collected and transported to ditches so they could be washed and later dried on land. The colour of the leaves gave indication on the quality of the 'processed' seagrass. The best quality was when the dry leaves were black (Bartels et al., 2016). If they were a brown colour, it meant the leaves still had a very high content of salt (Bartels et al., 2016). The high-quality leaves were used directly after undergoing the process or stored in sheds for future use (Bartels et al., 2016).

A layer of seagrass served as shock absorption of waves at the seaside of the dike. Seagrass was compressed in horizontal layers together with wood, forming a 1 - 7 meters wide wierriem (Figure 8). This layer provided a compact and tight protection comparable to a brick or stone wall structure (Bartels et al., 2016). Every 3 years, dikes had to undergo maintenance due to the shrink factor caused by compression (Bartels et al., 2016). The maintenance included adding new seagrass to increase the dike's height.

Unfortunately, during 1731 and 1734, a plague of the clam Tedero navails caused trouble with all dikes in the Netherlands. The mollusc destroyed the wood that supported the seaside barrier with seagrass. After years of struggle, the Dutch came up with the solution of substituting the wood with stones (Bartels et al., 2016). Then, in the early 1900s the use of seagrass in dikes decreased just as the species stopped growing locally.

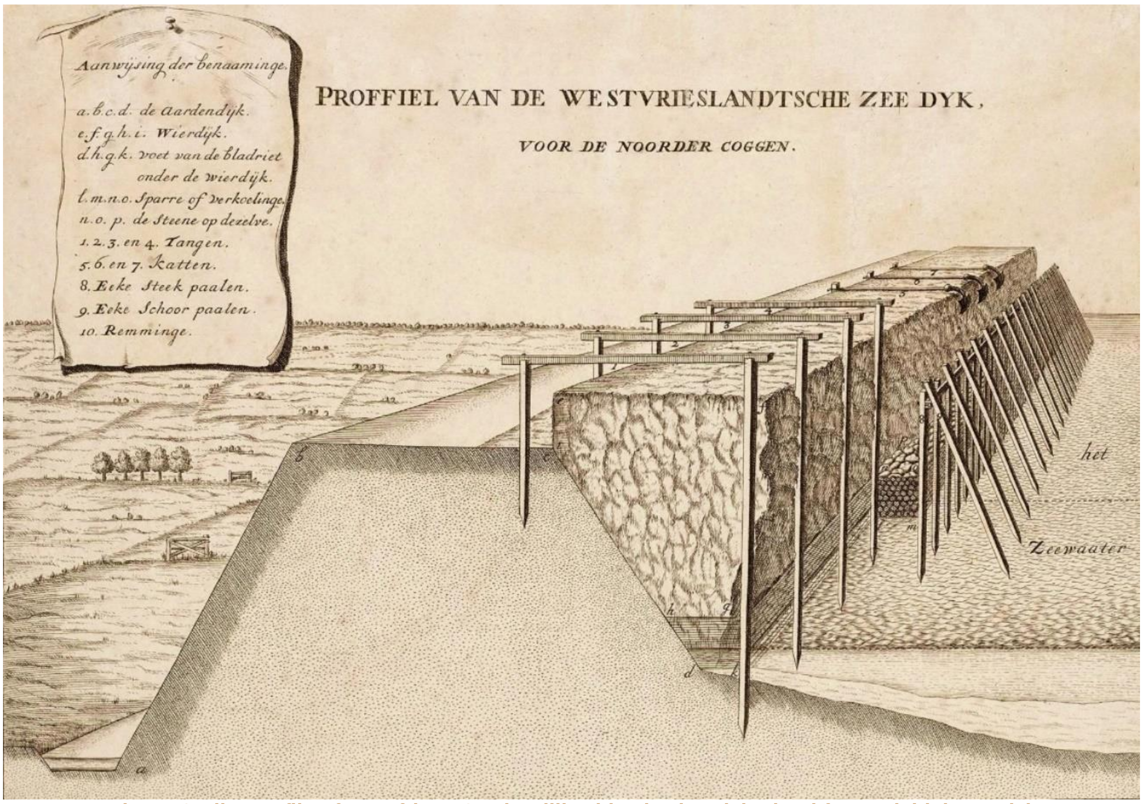

Figure 8 Dike profile of Westfriese Omringdijk with wierriem (obtained from Michiel Bartels)

5.5 FILLING FOR MATTRESSES & CUSHIONS

The first use of seagrass for resting dates back 100,000 years ago in France. Inhabitants in the Lazaret cave used *P. oceanica* leaves to sleep on (C. Boudouresque et al., 2012). At some point it was also used for cattle bedding as it was identified that less parasites will invade in comparison with using straw (Borum et al., 2004). More recently, in the 19th century, communities in the Netherlands started filling mattresses and cushions with seagrass (Bartels et al., 2016). These seagrass mattresses were even used in hospitals (comment by Frans Segers) and jails/police station cells (Bartels et al., 2016). The phenolic acid contained in the seagrass leaves are the reason why pests/vermin will not thrive so easily in the material (See Chapter 4.2.3) (C. Boudouresque et al., 2012).

5.6 OTHER APPLICATIONS

Additional uses for *P. oceanica* and *Z. marina* leaves were found in literature, although there were not vast details. Either literature was not available or authors concluded further experiments should be performed before favouring the innovative application. For this reason, these other applications will be briefly mentioned in this subchapter.

Other traditional uses for *P. oceanica* leaves include using them as packing material, to make shoes, to weave furniture, and even for medicinal use (Borum et al., 2004; C. Boudouresque et al., 2012; Riosmena & López, n.d.). Merchants in Mediterranean countries covered fragile items, such as glasswork, with seagrass to protect them during transportation (Borum et al., 2004). This practice was particularly popular in Venice, for which *P. oceanica* leaves can also be known as "Venetian straw" (C. Boudouresque et al., 2012). Another possibility for seagrass leaves was discovered in ancient Egypt times. It is believed that people made shoes with the fibres of the sea balls, also called aegagropiles(C. Boudouresque et al., 2012). Egyptians also attributed healing properties to this seagrass specie. It is mentioned as a popular product in old botanics handbooks and was used for sore throats and skin problems (C. Boudouresque et al., 2012). Borum et al. (2004) also stated that *P. oceanica* was used for the alleviation of skin diseases (i.e. acne) and pain in legs caused by varicose veins. In addition, on the other side of the world, in Mexico the Seris used *Z. marina* to fill balls made from animal skins and to make woven furniture similar as to rattan (Riosmena & López, n.d.).

Moreover, other novel applications for seagrass include: biochar production, paper production bio-coal production, landfill biocovers, dune restoration, transplants for seagrass meadow's restoration and as compost in reed-bed systems (Balestri et al., 2011; Chubarenko et al., 2021; Davies et al., 2007; Otero et al., 2018). In most of these applications, seagrass was not solely studied. Instead, beach wrack was analysed; meaning the biomass not only includes seagrass but also debris, sand, algae and other marine plants.

On the Island of Rugen in Germany, beach wrack was collected to value the possibility of converting it to bio-coal, a carbon neutral fuel produced by pyrolysis (Chubarenko et al., 2021). Bio-coal is comparable to lignite and can be used in all traditionally coal-fired processes (Chubarenko et al., 2021). The organic material used for bio-coal production was made up of green garden waste, waste food waste, and beach wrack in the ratio 15:3:1 (Chubarenko et al., 2021). Other application of beach wrack has been studied in landfills of the Municipality of Køge in Denmark. It was proposed to use beach wrack containing *Z. marina* as compost material in biocovers. Biocovers aim to use methane-oxidizing microorganisms to convert methane from landfills to CO2, a greenhouse gas with a lower **Global Warming Potential** (Chubarenko et al., 2021). A mixture of garden waste, beach wrack and horse manure in the ratio 1:1:1 has resulted in the reduction of 4 kg of methane per hour (Chubarenko et al., 2021). However, Chubarenko et al., (2021) state that it is still unclear if beach wrack will perform similarly in a larger scale.

Another innovative practice is the restoration of seagrass meadow using fragments of washed up *P. oceanica*. Balestri et al., 2011 identified that fragment survival rates and regeneration have the capacity to r-establish when introduced into the field. The advantage of this application compared with traditional seagrass meadow restoration techniques is the large availability of fragments, zero impact on existing population and low collection efforts (Balestri et al., 2011). Also, beach wrack, algae or seagrass leaves have been used for dune restoration in Hyeres-de-Palmiers, in France (Otero et al., 2018). The technique “mille-feuilles” consists of placing layers of 30 to 40 cm of *P. oceanica* covered with sand to stabilize dune walls (Otero et al., 2018).

6 ENVIRONMENTAL EFFECTS

As mentioned in Chapter 4.1, *Z. marina* and *P. oceanica* shed their senescent leaves annually or interannually, a large portion of which exported out of the seagrass meadows. These leaves accumulate on European shores and form deposits, called banquettes, that fulfil important ecological and environmental functions. Common practice is to remove and landfill seagrass banquettes from beaches close to urban centres, since they are the source of foul decomposition odours and fires (in summertime). Moreover, tourists interpret seagrass wrack as an indicator for poor beach condition. The removal of seagrass wrack is done with heavy machinery that severely impacts the shoreline and contributes to greenhouse gas (GHG) emissions due to fuel consumption.

Roig i Munar et al. demonstrated that further beach erosion occurred during stormy weather after *P. oceanica* banquettes were mechanical removed (Roig I Munar & Prieto, 2005). This indicates that seagrass banquettes consisting of either *P. oceanica* or *Z. marina* prevent beach erosion, especially during the occurrence of storms. Several studies have shown that seagrass banquettes effectively trap sand and reduce wave energy (Chessa et al., 2000; Simeone & De Falco, 2012; Strandressource, 2019). Additionally, large scale beach cleaning does not only remove seagrass wrack, but also invertebrate species, plant propagules and sand (Defeo et al., 2009). During industrial beach wrack removal along the Baltic coasts, 50-90% of the removed mass consists of sand trapped in, our surrounding the beach wrack (Mossbauer et al., 2012). Seagrass banquettes can retain an average of 93 kg/m^3 sediment and the removal of seagrass banquettes in Sardinia (Italy) resulted in a loss of sediment between 0.5 and 1725 m^3 per beach (De Falco et al., 2008). Leaving seagrass wrack on the beach protects the coastline, since less sediment is removed from the shore by wind and waves. However, according to Gómez-Pujol et al. this is not always the case. The protective role of *P. oceanica* banquettes should be reconsidered for semi-enclosed beaches since there is a large variability in banquette deposition and permanence. Therefore, the beach is often not protected by seagrass banquettes when stormy weather occurs (Gómez-Pujol et al., 2013).

The removal of seagrass wrack from beaches can also have a negative effect on beach, foredune and seagrass meadow ecosystems. Seagrass banquettes of both *P. oceanica* or *Z. marina* are a source of nutrients such as nitrogen (N), organic carbon (C) and phosphorous (P). They form the base of a **detritus** food web and are home to a rich macrofauna consisting of **gastropods**, **annelids**, **crustaceans** and insects that live of the provided nutrients (C. F. Boudouresque et al., 2015). Moreover, seagrass that is transported further inland, provides nutrients to the foredune and can induce germination of other marine plants (Nordstrom et al., 2011a). As a physical structure, seagrass banquettes provide shelter for (larger) predators and detritivores against environmental conditions. The nutrient rich seagrass wrack can also be a challenge for eutrophication prone areas such as the Baltic sea (*Baltic Sea Action Plan – HELCOM*, n.d.-b). Nutrients released by decomposition of the seagrass wrack can be re-released and transported to eutrophicated areas which can lead to oxygen depletion and death of marine life.

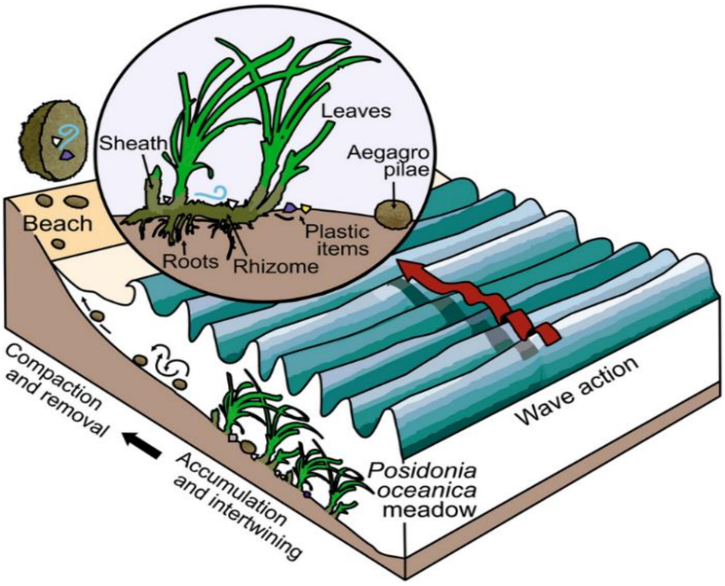

Figure 9 Trapping of plastic in Neptune balls originating from P. oceanica (Sanchez-Vidal et al., 2021)

The aforementioned effect of seagrass banquettes on ecosystems applies to the discarded senescent leaves of for instance *P. oceanica or Z. marina*. However, *P. oceanica* also produces spherical Neptune balls (Aegagropilae) that wash up on Mediterranean beaches. The burial process of dead *P. oceanica* releases lignocellulose rich fibres from the leave sheaths. These fibres intertwine and roll up by wave action in spherical Neptune balls (Figure 9). These balls are shown to provide a novel ecosystem service by removing large quantities of marine microplastics from the Mediterranean sea. Sanchez-Vidal et al, found up to 1,470 plastic items per kg Neptune ball that consisted mostly of filament and fibre fragments (65%) (Sanchez-Vidal et al., 2021). Washed up leaf banquettes also contain plastics but in significantly lower quantities than Neptune balls. These plastics likely originate from the water surface and are washed ashore together with the *Posidonia leaves* (Sanchez-Vidal et al., 2021).

On the other hand, seagrass wrack can also have a negative impact on the environment. Seagrass wrack undergoes microbial breakdown, which releases significant amounts of GHG emissions, such as carbon dioxide (CO_2) and methane (CH_4), in the atmosphere. Coupland et al. estimated that seagrass wrack on Australian beaches had an emission rate of 6 μmol CO_2 m^{-2} s^{-1} (Coupland et al., 2007). In addition, Misson et al. demonstrated that methane (CH_4) emissions were present during the decomposition of seagrass wrack and that the amount depended on the salinity and environmental temperature (Misson et al., 2021). Annual GHG emissions from seagrass wrack globally was estimated to be between 1.31 – 19.04 Tg C yr^{-1} (equal to 0.63 - 9.19 million Chinese citizens), and is depended on intertidal wetting. In the presence of water, seagrass decomposition releases up to 72% more GHG in comparison to dry wrack (بارانی, n.d.). This is likely due to the leaching of soluble materials and higher microbial activity because of more suitable growth conditions (Dick & Osunkoya, 2000; Nicastro et al., 2012). Lastly, heavy metals are deposited on the beach that were accumulated in the roots and leaves of seagrass due to **anthropogenic** pressures (Villares et al., 2016).

Subsequent to the seagrass removal, the 'waste' is transported to landfills. Although this management practice is undesired, as stated in the European Waste Framework Directive; legislation in some countries, such as Italy, endorse the treatment of seagrass wrack as urban waste (*Waste Framework Directive*, n.d.) instead of a natural and valuable resource. Landfilling is costly for local municipalities (80 €/t), releases high amounts of GHG emissions in the atmosphere by decomposition and removes nutrients (especially organic C) from the beach. Therefore, applying seagrass wrack as a valuable resource could be an environmental and social friendly alternative to the current beach management.

As discussed in Chapters 5 & 6, there are many possible applications for seagrass and every application can have a different environmental effect. For instance, the production of compost and biogas (anaerobic digestion) from *P. oceanica* wrack significantly reduced the environmental impact with -70% and -90% respectively, in comparison to landfilling. In the same study, they found that a combination of ecological restoration (leaving seagrass on the beach) and anaerobic digestion (50/50) had the lowest environmental impact in comparison to landfilling (Balata & Tola, 2018). However, this would have a negative impact on the economic balance due to a potential decrease in tourism. Otero et al. estimated the costs of seagrass wrack on touristic beaches to be €2,98 per m^2. This shows that some environmentally beneficial applications are not likely to be applied. Other applications such as house insulation or additive in bio-composites can also theoretically reduce environmental impact by replacing a polluting material such as fibre glass (insulation) or fossil-based polymers (composites). However, a possible bottleneck might be the collecting, processing and cleaning of the seagrass wrack, as conventional collection methods with heavy equipment often prevent high-value applications due to contamination with sand, algae and litter (Aldag et al., n.d.).

It is safe to say that the application of seagrass wrack as a resource has less of an environmental impact than landfilling. However, there are still similar disadvantages such as coastal erosion and nutrient removal that do not occur with ecological restoration management (leaving the seagrass on the beach). An alternative approach would be to collect part of the seagrass wrack as a resource and leave the rest on the beach. The advantages and disadvantages of these different management practices are listed and summarized in Table 8.

Table 8 Environmental and economic advantages of 3 different management practices

Management practice	**Landfill**	**Ecological restoration**	**Resource application**
Advantages	+ No processing + Not labour intensive + Existing infrastructure	+ Nutrient availability for beach flora and fauna + Prevention of beach erosion	+ Less local costs or extra income + Reduced environmental impact
Disadvantages	- GHG emissions due to decomposition - Nutrient removal - High costs (80€/t) - Beach erosion	- Reduced tourism income - GHG emissions - Eutrophication	- Beach erosion - Nutrient removal - Requires pre-treatment and/or different collection methods

7 DISCUSSION & RECOMMENDATIONS

Washed up seagrass is an economic and environmental problem in many touristic beaches within the European Union. The tourism industry perceives beach wrack negatively and often opts to its removal (Otero et al., 2018). The most common management after its collection is landfilling. This practice is least preferred according to European Waste Directive, because of greenhouse gas emissions, land use demand, costs, and the lack of valorization of the material (Mainardis et al., 2021).

Concerned with the previous issues, ArtEZ Future Makers and the consultancy team explore the possibilities of using seagrass wrack found in European beaches as a sustainable resource. The report analyses the two most common species of seagrass found in Europe: *Z. marina* and *P. oceanica*. Through literature review and consultation of experts, the biological, chemical, and physical characteristics of the two species of seagrass were obtained. These properties were cross-referenced with historical applications and possible novel uses, and later evaluated to give an overview of the environmental challenges and opportunities of the use of the material.

Although seagrass wrack is present all around the globe, the focus of this report lies on the affected areas in mainland Europe. Z. marina is the most abundant seagrass in beachwrack along the Atlantic and Baltic Sea coasts, while P. oceanica takes up that role along the coast of the Mediterranean Sea. Seagrass species differ in composition and morphology, which should be kept in mind in further applications.

7.1 MORPHOLOGY AND PROPERTIES OF *Z. MARINA* AND *P. OCEANICA*

Z. marina forms long, narrow leaves with a short lifespan, sheds its leaves twice a year and has a moderate fibre content. It is capable of rapid horizontal expansion through the formation of horizontal rhizomes. The chemical composition shows that Z. marina is suitable for compositing or pyrolysis (biochar) due to its C/N ratio (23.1). Z. marina has a relatively low lignin content (5%) which makes application in papermaking not ideal. Fibres of Z. marina are structurally different for terrestrial plants and are promising for application in reinforced composites but still inferior to the currently used fibres. Furthermore, the thermal conductivity and specific heat capacity of Z. marina leaves are comparable to conventional insulation materials but require a higher density. Secondary metabolites of Z. marina can be used for pharmaceutical applications but also prevent mould formation when it is used as insulation or filling. The morphology and properties of Z. marina are affected by local growing conditions. Along the European Atlantic coast, a clear decrease in fibre concentration can be observed from colder climates in the north towards the warmer southern climates. For applications that rely on fibre content or lignocellulosic biomass this means that Z. marina harvested from northern beaches offers a greater potential.

P. oceanica has shorter, broader leaves than *Z. marina*, that are shed once a year in late autumn and reach higher fibre contents towards the end of their lifespan. Besides leaves, Neptune balls that are formed from the fibrous remains of detached leaves also wash up on the shore. Absence of organic contaminants, such as seaweed, make them easier to work with than banquettes. However, both forms contain micro-plastics which should be removed before using the seagrass for paper applications (Sanchez-Vidal et al., 2021). The chemical composition shows that P. oceanica leaves are not suitable for composting or pyrolysis due to their C/N ratio (49.5). In contrast, the Neptune balls have a lower C/N ratio (22.4), which makes them more suited for composting applications. The P. oceanica leaves and Neptune balls have high lignocellulosic fractions of 86% and 91.6% respectively, which decreases valorisation by anaerobic digestion but boosts humus formation. The high lignin contents of both the leaves (27%) and balls (29.8%) show a high potential for the papermaking industry. Fibres of P. oceanica (balls and leaves) were successfully used to reinforce materials but no information was available on the individual fibres. It is claimed that Neptune balls give the best heat protection in the summer as insulation but similarly as Z. marina, a higher insulation density is required and installation is still expensive (0.8 €/kg).

7.2 ENVIRONMENTAL FACTORS AND GROWING CONDITIONS

Even within a single species, the quality and the characteristics of washed up biomass can vary depending on the growing conditions of the seagrass and decomposition that occurs before and after washing up. A primary determinant of leaf characteristics in Z. marina is the local climate. With increasing temperatures and strong hydrodynamic forces, Z. marina plants form smaller, more flexible leaves that contain significantly less fibers than fellow species in colder climates. With up to twice as much fiber content than their southern counterparts, it is advised to use *Z. marina* harvested in colder climates for applications relying on fibers. In applications that require smaller or larger leaf segments, one should pay attention to the growing depth of the meadows (from which the seagrass detached from) as it influences most characteristics of the seagrass. Upon detachment of the plant parts, decomposition by microorganisms starts.

Advanced degradation of leaf remains on vertical rhizomes of P. oceanica, leads to the formation of fibrous material that form the majority of Neptune balls. When these balls or detached leaves wash up on the shore, further decomposition can take place. It is therefore important to take note of the time of harvest to obtain material of the utmost quality. Although the lignocellulosic matter can usually take quite a while to fully decompose, decomposition of the tissue surrounding the fibres can be quick. To obtain the maximum amount of biomass, harvesting needs to take place as quickly as possible after it washes up on the shore. Decomposition can be slowed down by moving the seagrass wrack further inland to reduce the moisture content and thereby the decomposition rate. As lignocellulosic fibers are relatively resistant to decomposition, harvesting time is especially of importance to applications that rely not on the fibers but, for instance, secondary metabolites or total biomass.

7.3 HISTORICAL APPLICATIONS AND THE ENVIRONMENTAL IMPACT

Throughout the literature review, it was found that washed up seagrass isn’t only a nuisance, but it also provides ecosystem services. These services include: erosion prevention, nutrients provisioning and shelter provisioning for marine life (Nordstrom et al., 2011b). These ecosystem services are so relevant that the recommendation in a sustainable management of beach wrack is to leave the seagrass on the coast for ecological restoration (Otero et al., 2018). However, if the presence of seagrass on beaches is causing strong disturbances in the tourism sector, then it can be reasonable to collect and manage this waste stream (Otero et al., 2018).

As mentioned before, the most common management practice is to landfill seagrass wrack. According to the European Union’s Waste Framework Directive, if a material is already regarded as waste, the next preferred option after disposal is recovery. Resource recovery means the waste serves a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function (Waste Framework Directive). The advantages of resource recovery against landfilling are the reduction of environmental impacts and a decrease in costs or even extra income (See Chapter 6). Depending on the specific application, additional benefits can be identified. The possible uses of seagrass wrack are wide and can be broadly classified in two categories: historical applications and novel applications. The historic uses of seagrass help to understand how this material has been processed before and can provide foundation for new applications. Novel applications are currently being studied and still further research to reassure their safe and successful implementation.

Traditional applications for seagrass are varied and include compost, insulation, building material for houses and dikes, food and feed, filling of mattresses and as medicine. Specific physical and chemical properties give seagrass valuable qualities for each one of these applications. For instance, using seagrass for mattresses is one of the oldest practices found. Seagrass was very practical and hygienic due to the phenolic acid and zosteric acid in the leaves. Another traditional use was composting. The nutrient content of compost from seagrass leaves is higher than in organic waste compost (Horst Sterr et al., 2019). Or, regarding insulation, seagrass can protect similarly as modern materials such as expanded polystyrene, but without any additional chemicals. On the other hand, novel applications include biochar production, paper production, bio-coal production, landfill bio-covers, dune restoration, transplants for seagrass meadow's restoration and as compost in reed-bed systems.

Utilizing collected washed up seagrass as a resource is preferred compared to landfilling. However, using seagrass wrack as a sustainable material comes with its challenges. Temporality is a major issue when it comes to seagrass (Chubarenko et al., 2021). As mentioned in Chapter 4.1, leaves of *Z. marina* are shed in early spring and in early fall while *P. oceanica* from fall to winter. So, if ArtEZ Future Makers would utilize this resource, there should be careful planning on when and where the collection could be done. As mentioned previously in this discussion, decomposition of the seagrass wrack, especially the interfibrous tissue, can happen quickly and affect the characteristics of the seagrass. Depending on the intended application, it can therefore be very important to harvest seagrass quickly after it washes up on the shore. Also, the commissioner should also take into consideration that seagrass meadows underwent a decline at the beginning of the 20th century. Many areas have been restored and recovered, but others, such as in Dutch coastal waters, are still highly threatened. The Blue Carbon Initiative and other environmental projects are currently trying to reintroduce the species in Dutch waters but are often underfunded (van Duren & van Katwijk, 2015). The commissioner should be aware of the situation and cautious of another anthropogenic or natural caused event that could affect seagrass meadows, thus the availability of washed up seagrass on European beaches.

Another issue that was identified is the collection and processing of the seagrass. Collecting all seagrass wrack on a beach will cause a decrease in nutrient availability and an increase of erosion. To reduce this risk, it is recommended for the commissioner to execute the collection after storm season or to consider leaving at least 10 cm of banquette in the beach (Otero et al., 2018). Also, the frequency of heavy machinery used should be minimized as it damages the coastal ecosystem (Chubarenko et al., 2021). Less intensive methods, such as manual pick up or lighter vehicles, are recommended for collection. The vehicles should be driven at least 5 m from dunes and should avoid local vegetation (Otero et al., 2018). Once collected, the commissioner should also consider the machinery for filtering and further processing the material depending on the chosen application. It is expected that sand and waste removal will be necessary in most applications, as each wrack can be up to 85% sand and is often mixed up with other materials such as plastics and other organic material (Otero et al., 2018).

Additionally, it is recommended for ArtEZ Future Makers to consider the local legislation of the beach they wish to collect washed up seagrass form. Boudouresque et al., 2012 expressed that valorisation of dead *P. oceanica* leaves is illegal in France. So, further research on technical and legal aspects of specific locations in Europe is suggested. Once the commissioner decides on which application, they wish to give the washed up seagrass, they should be aware to follow any quality requirements regarding the final product. Often, products need to adhere to pre-set standards prior to product release.

7.4 CLOSING REMARKS

The sustainable collection and use of washed up seagrass as a resource matches European Union's Circular Economy model because there is reuse as material, waste prevention, having a safe and clean material, and it is locally produced. ArtEZ Future Makers can not only promote environmental benefits with the use of this new material, but also generate awareness to the public. It breaks paradigms of material sourcing and opens the possibilities in a variety of industries. Additionally, it gives the opportunity to relate economic activities to this marine plant, just as done historically. As well, using washed up seagrass might draw attention to restoration efforts to seagrass meadows and in some way even help increase funding to these projects.

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9 APPENDICES

9.1 APPENDIX 1: STAKEHOLDERS LONG-LIST

Latents:

Tourism industry: This industry has a high power over the seagrass wrack collection because the material is a nuisance to both beach users and tourists. Tourists and the touristic industry view beach wrack as negative (Otero et al., 2018). Although, their interest for this project is low, since they likely only care for the removal of beach wrack, not the application.

Authorities of EU beaches: This industry has a high power over the seagrass wrack collection because the material is a nuisance to both beach users and tourists. Moreover, the authorities of EU beaches make high costs to remove the beach wrack and a local solution that increases the value of beach wrack might be interesting to them.

Promoters:

Policy makers: High influence over seagrass wrack collection and various industries (textile, fertilizer etc.) on a regional, national and EU level. There is some interest in the application of seagrass wrack in products because it aligns with the sustainable development goals.

Environmental NGO's: Relatively high influence due to the ability to create awareness among the public and provide independent science-based policy advise on seagrass. Relatively high interest since seagrass meadows are ecologically beneficiary, and seagrass related consumer products might inform and sensibilize the public and demonstrate potential.

Designer Brands: Relatively high influence due to experience and capital in fibre processing. Relatively high interest because the industry must become sustainable sooner than later. Seagrass as a sustainable bioresource for fibres and/or other products aligns with their long-term goals.

For example, the Product Design department of Fatboy has expressed their interest in the use of biomaterials for the fillings of their bean bags/chairs (comment from visit to the company's Headquarters).

ArtEZ Future Makers: This Centre of Expertise Future Makers has a relatively high power due to their cooperation with partners such as research centres, governments and companies. Moreover, it has a very high interest in this project because they aim to make value chains in fashion and textiles more sustainable, which can potentially be realised with seagrass.

Research institutes: Research institutes have the most knowledge on seagrass and therefore power. Moreover, application of seagrass interests them because it can help the transition of industries towards a more fair, clean and sustainable future.

Apathetics:

Compost/fertilizer industry: This industry has low power and interest in the value chain of seagrass because composting of seagrass only makes up a small part of their industry.

Consumers: Individual consumers have low power and interest in the value chain of seagrass because they can only make a small difference with their consuming behaviour and are generally not aware off seagrass waste.

Defenders:

Blue Carbon projects: Might have interest in this project because it could emphasize the importance of seagrass meadows as blue carbon ecosystems which aligns with their message. However, their power will be limited because seagrass wrack is outside their scope and their focus will be on the seagrass meadows.

Innovative designers: These designers have a high interest in seagrass because it could become a novel and sustainable application in their designs. However, their power is limited because they have limited influence on the market and seagrass wrack collection.