Regional variations in the chemical composition of fresh and composted beachcast on the island of Gotland, Sweden – considering future treatments

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Abstract

Harvesting beachcast from coastal zones to use the biomass in agriculture or horticulture could mitigate eutrophication while contributing to resource substitution of fossil-based inputs in food production. As such, beachcast holds great resource potential in a bio-based circular economy, but its chemical properties prove challenging, and more research is required to develop treatment techniques that will allow the realisation of such a system. We compiled results from chemical analyses of fresh beachcast from a database within the marine policy scheme, LOVA, in Gotland, Sweden, to study local and seasonal variations in macronutrients, C:N ratio, and Cd content. This data complemented with analyses of fresh and composted beachcast (passive pile treatment), for which the contents of macronutrient, ammonium, nitrate, and Cd, were measured, calculating C:N ratios and maturity indices (NH_4^+-N/NO_3^-–N). The results confirm that regional variations in the above-mentioned properties require investments in treatment techniques and strategies to make beachcast usable.

Keywords: *beachcast, chemical composition, treatment, waste-to-resource conversion, sustainable resource management*

1 Introduction

Beachcast (predominantly washed-up algae and seaweed) is available in excess in many coastal areas worldwide. It is often removed to avoid damaging impacts on the regional/local economy (e.g. loss of tourism resulting from the nuisance effect) and the environment (e.g. harmful effects of eutrophication) (Bougarne et al., 2019; Mainardis et al., 2021; Mossbauer et al., 2012; Nelson et al., 2015; Simeone et al., 2013; Weinberger et al., 2019). At the same time, the sustainable utilisation of beachcast as fertiliser is expected to play an essential role in agroecosystems in coastal areas in the near future, serving as a regenerative alternative for the substitution of hydrocarbon-based primary resources in agriculture (Emadodin et al., 2020; Eyras et al., 2008; Illera-vives et al., 2020). According to the FAO (Food and Agricultural Organisation of the United Nations), future sustainable food production requires the elimination of chemical fertiliser input by 2050, the creation of nutrient cycles, and the returning of carbon in the form of organic material to soils, with each of these factors identified as critical for a sustainable food system (FAO, 2018). Therefore, from a system-wide perspective, providing incentive to use this nutrient and carbon-rich biomass sustainably that theoretically holds great resource potential in a bio-based circular economy (CONTRA, 2021; Milledge & Harvey, 2016; Rudovica et al., 2021; Sinha et al., 2022; Smetacek & Zingone, 2013; Thomas et al., 2021).

Multiple areas of use and treatment techniques for beachcast are being researched, including traditional composting in passive piles (e.g. windrows) to produce fertiliser (Illera-Vives et al., 2013b; Madejón et al., 2022), as well as more technically advanced uses such as biogas (Barbot et al., 2016; Milledge & Harvey, 2016) and biochar production (Katakula et al., 2020; Macreadie et al., 2017). However, recent research favours simple composting as opposed to the more advanced solutions because of its economic and environmental advantages (Illera-Vives et al., 2013a), as well as technical advantages (García & Loring, 2022) when transforming the biomass into an agricultural resource.

In practice, however, the efficient use of beachcast is largely lacking, with huge amounts of potential resource material going to waste, while management practices and policy development concerning beachcast are hindered by a lack of knowledge regarding the fresh beachcast material (Chubarenko et al., 2020; Milledge & Harvey, 2016; Mossbauer et al., 2012; Nathaniel et al., 2023). Moreover, research on the agricultural use of algae and seaweed has predominantly focused on derived products (extracts, liquids, powders, concentrates), whereas there has been much less study on the use of drift seaweed and algae, i.e. beachcast, as a biofertiliser (Illera-vives et al., 2020). This calls for more research so that the associated challenges can be resolved.

As with all fertilisers, balancing the macronutrients (NPK) is fundamental to optimising plant nutrient availability. In contrast to chemical fertilisers, the content of all bio-based sources varies, affecting the recovery potential (Vaneeckhaute et al., 2018). This is also true for beachcast, which is prone to natural variations depending on location, season and species abundance, and mapping the variations is encouraged in order to be able to predict the chemical content (Chubarenko et al., 2020; Franzén et al., 2019; Michalak et al., 2016; Villares et al., 2016).

Moreover, as for all biofertilisers, the C:N ratio affects the composting process and plant nutrient availability (Cáceres et al., 2018; Crohn, 2016). Considering the C:N ratio of beachcast material, studies have shown that it is lower even than the suboptimal level for mineralisation processes (varying between 1/10 and 1/20) (Han et al., 2014), but knowledge is scarce and significant variations between regions are to be expected due to the varying content of macronutrients in the fresh beachcast material .

Furthermore, the expected risk of cadmium (Cd) contamination (of both soils and crops) from the use of recovered biowaste streams in agriculture (Barrow, 2000; Römkens et al., 2018) is also confirmed as a risk for the agricultural use of beachcast (Franzén et al., 2019; Greger et al., 2007; Nathaniel et al., 2023). In general, management policies governing Cd in soils and crops stress the importance of minimising Cd inputs to the soil (Barrow, 2000), and in the context of collecting the mineral content of biowaste, it is essential to know the origin and concentration of heavy metals in the raw materials at the beginning of the biological processes (Huerta-Pujol et al., 2011). Recent EU legislation and strategy to reduce the Cd content in fertilisers, food, and feed has specified the Cd threshold for biofertilisers as 1.5 mg/kg (EU Fertilising Products and Amending Regulations, 2019). Meanwhile, replacing non-renewable fertiliser sources with recovered waste products as specified in EU policy targeting phosphorus cycling has promoted the use of local alternatives for low Cd fertiliser sources (Ulrich, 2019). Naturally, the Cd content will vary with local conditions and treatment procedures, requiring case-specific knowledge to enable such a transition in fertiliser sourcing. This requires studying of the Cd content of beachcast, including the changes in Cd concentrations that occur during treatment (Franzén et al., 2019).

A relevant study case is the regional beachcast management system in Gotland, Sweden: In an attempt to reduce the nutrient load in the Baltic Sea, a Swedish national policy (LOVA) supports beachcast harvesting, which has to a large extent been implemented on the island of Gotland (HaV, 2022). The system has encouraged the use of beachcast in regional agriculture, with the standard treatment practice in the region being passive pile composting. (Nathaniel et al., 2023).

Therefore, the aim of this study was to provide data (on macronutrients, C:N ratio and Cd content) at various locations on the island of Gotland, Sweden, with the data being affected by location, season and possible changes in the treatment of the passive piles, as well as species abundance in the beachcast. The aim of this paper is to provide knowledge on the use of beachcast in agriculture that can assist policy-making on (re-)introducing this marine bioresource into the circular economy.

2 Materials and Methods

2.1 Study area and management system

The island of Gotland is located in the Baltic Sea (57° 29' N, 18° 32' E). Of its total area of 3,135 km2, 36 % is used for agriculture. Gotland has a long tradition of using beachcast as a fertiliser and for soil improvement (Lythberg, 1799; Säve, 1938; von Linné, 1741). Although abandoned in today's intensive agricultural practices, this resource is still available. The amount available has increased due to the eutrophication of the Baltic Sea (Weinberger et al., 2019) and rising sea temperatures due to climate change (Ref.). However, regional data from Gotland to support this is not available. Access to beachcast on Gotland today is mainly due to the Swedish national policy scheme LOVA (Hav och vattenmyndigheten, 2015) initiating and subsidising projects to curb eutrophication in the region. It has resulted in 89,287 tonnes of FW beachcast being collected over ten years of activity in different local projects on Gotland. This amount is equivalent to a nutrient reduction and content of 466,045 kg nitrogen (N) and 34,696 kg of phosphorus (P) (Söderqvist et al., 2021) – primary macronutrients that could potentially supply agricultural production.

2.2 Data collection, sampling and chemical analysis

The first dataset presented in this study consisted of chemical analyses of beachcast conducted as part of the LOVA scheme on Gotland, a database administered by regional authorities, the Gotland County Board (Swedish: Länsstyrelsen Gotlands län). The data was previously unprocessed and thus used in this study to provide knowledge on local variations in beachcast macronutrients and Cd content.

To improve knowledge regarding the agricultural application of beachcast, additional samples of fresh and composted beachcast material (for analysis of nutrient and Cd content) were conducted, providing a second dataset to complement the existing one from the LOVA scheme (see 2.2.2 below).

2.2.1 Compilation and analysis of chemical samples from harvesting locations of the LOVA scheme

Chemical analyses of the beachcast material from the LOVA scheme sampling have been conducted in around 20 locations over the period 2012-2023 on Gotland. Sampling and analyses have been conducted 1-2 times a year from each harvesting location, with the procedure of collecting a minimum of 500 g of beachcast in 3-5 spots from the stretch of beach being harvested, pooling the samples and sending it to Agri Lab AB (Uppsala, Sweden) for analysis. For complete instructions and procedure for collection, sampling and analysis provided by Gotland County Board, see Appendix A.

Statistical analyses of the variations in chemical content by location were based on the simplifying assumption that samples from different years served as replicates for each location. Therefore, only locations where sampling has occurred at least four times and at most six times during the years 2016-2021 are included in the analysis. Altogether eight locations were included: Alnäsaviken (Fårö), Kyrkviken (Fårö), Sandviken (Östergarn), Vitviken norra, Vitviken södra, Nisseviken, Kvarnåkershamn, Sandhamn (Fröjel) (Figure 1).

To include seasonality in our analysis, sampling dates were noted and classified by season, based on seasons defined as follows: spring (March-May), summer (June-August), autumn (September-November) and winter (December-February).

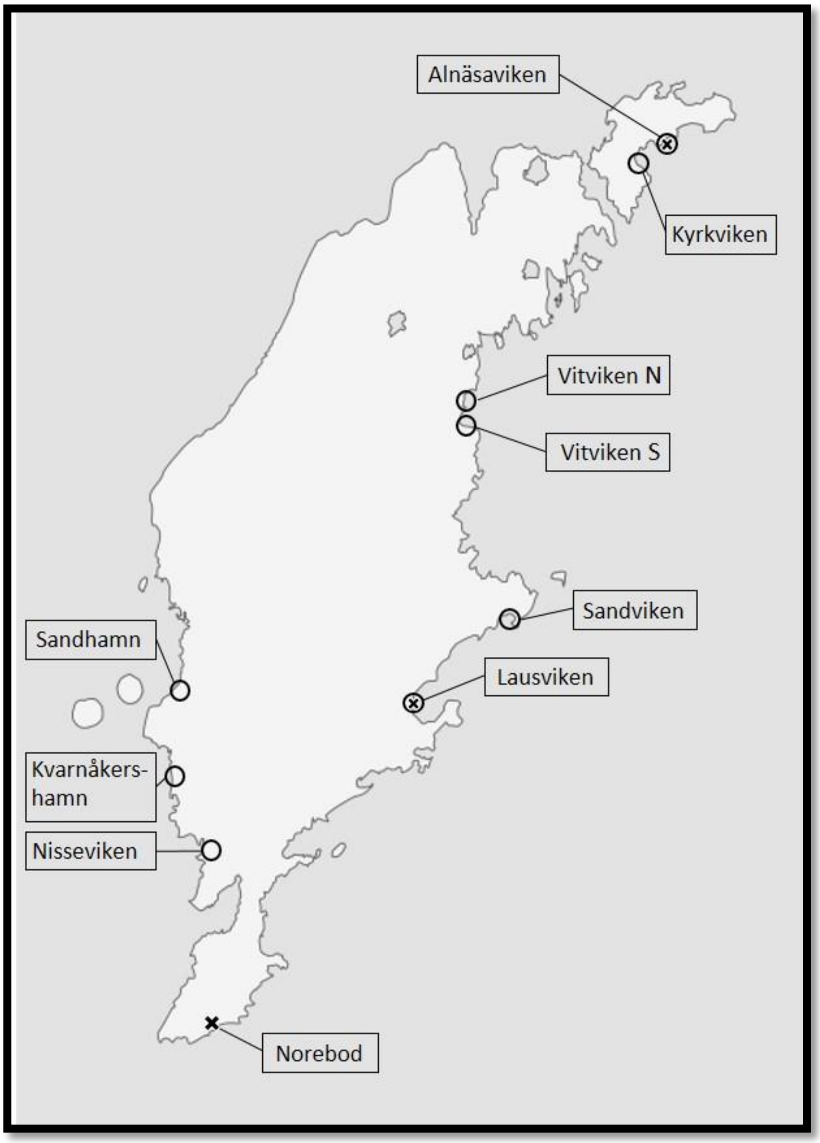

Figure 1. Map of Gotland showing the harvesting locations for chemical sampling of beachcast within the LOVA scheme that was compiled and analysed in this study (marked with circles, ○), as well as the sites where experimental sampling of fresh and composted beachcast was conducted (marked with crosses, ✖). The locations from the LOVA scheme sampling include Sandhamn, Kvarnåkershamn, Nisseviken, Lausviken, Sandviken, Vitviken South, Vitviken North, Kyrkviken, and Alnäsaviken. Locations for compost sites include experimental sampling for this study include Norebod, Alnäsaviken, and Lausviken.

2.2.2 Sampling and chemical analysis of fresh and composted beachcast from compost sites

Fresh and composted beachcast material was collected at three compost sites in Gotland (Alnäsaviken, Lausviken, and Norebod, see Figure 1) to analyse the chemical composition and species abundance. When beachcast is harvested as part of the LOVA policy scheme, the typical approach is to collect beachcast in piles slightly away from the shore where it decomposes (passive pile composting) and is rinsed, which has the additional effect of removing salts. Passive pile composting can resemble anaerobic composting conditions if the piles are not turned, or substrates are not added for aeration, but it is nevertheless an open system. The chosen pragmatic setup of the experiment means that compost management differed slightly between the three sites in respect of pile size, raw material content (e.g. macroalgae species), main harvest time, total composting time, and application time in fields (see Table 1).

Shortly after the harvesting of beachcast and its placing in piles to passively decompose (executed by NGOs and farmers) at the three chosen locations, we collected fresh beachcast at the same sites November-December 2019 (four replicates) from the beachcast bands (recently cast on the shore) close to the piles (maximum 30 meters). Approximately three to four months after the collection of fresh beachcast, four samples of the composted material were collected from the piles. The samples were collected about 0.5 metres down into the piles, at a height of 1 metre above ground, one in each direction (North, East, South, and West). Henceforth, the fresh and composted beachcast samples from compost sites are referred to as the 'compost site samples'.

Species abundance in the fresh beachcast samples collected for chemical analysis was estimated as percentage average spatial coverage of main species/groups of species by visual estimation using a procedure similar to that used by (Franzén et al., 2019). The collected beachcast biomass sample was spread out on a 0.5 x 0.5 meter plot at the beach site where the average spatial coverage of the following species and groups was visually estimated by two observers (independently): *Zostera marina*, *Furcellaria lumbricalis*, filamentous red algae (e.g. *Polysiphonia*- and *Ceramium*-species), and a lumped group of less frequent species (for example *Ulva intestinalis*, *Cladophora glomerata* and *Potamogeton pectinatus*), referred to as other species.

All chemical analyses of the beachcast material from the compost site samples were performed by the accredited laboratory ALS Laboratories (Luleå, Sweden), measuring nitrate, nitrate-N, ammonium-N, phosphorus (P), potassium (K), cadmium (Cd), total C (TOC).

The dry weight was determined according to SS-EN 15934. The analysis of total nitrogen (N, Kjeldahl) was determined through the following methods: 100 mg/kg DW DIN EN 16169: 2012-11; nitrate 0.20 mg/L DIN EN ISO 10304-1: 2009-07; nitrate-N 0.10 mg/L DIN EN ISO 10304-1: 2009-07; nitrate mg/kg DW DIN EN ISO 10304-1: 2009-07; and ammonium-N 0.020 mg/L DIN EN ISO 11732: 2005-05. To determine the phosphorus (P), potassium (K) and cadmium (Cd) levels, samples of 0.5 g dry mass (additional drying at 50°C) underwent mineralisation using 5.0 ml of 69 % HNO3/H2O2 in Teflon bombs in a microwave oven, using an ICP-SFMS instrument, in accordance with SS EN ISO 17294-1, as well as ICP-AES, SS EN ISO 11885. Total C (TOC) was determined as per EN 13137: 2001-12.

The ammonium-N to nitrate-N ratio and C:N ratio were calculated based on the results. The value of the ammonium-nitrate ratio is an indicator of non-stable and non-mature compost (Cáceres et al., 2018). An index below 0.5 would be considered very mature; 0.5–3 indicates a mature product, and above 3 indicates immature compost (Cáceres et al., 2018). The ratio can also be used as an indication of phytotoxic elements because a ratio of less than 0.16 is also recommended to exclude phytotoxicity (Bernal et al., 2009), and above this value, direct use as compost may not be recommended.

Table 1. The sample specification of fresh and composted beachcast from compost sites, indicating the position of the passive piles, their size, distance to the sea, time of sampling, temperature and pH.

Sample specifications & Site	Norebod	Lausviken	Alnäsaviken
Position [coordinates]	56°55'40.8"N 18°15'09.7"E	57°18'19.7"N 18°40'03.0"E	57°56'04.6"N 19°10'19.3"E
Size: height, length, width [m]	1.7 x 4 x 3	2 x 5 x 5	2.3 x 6 x 5
Distance to the sea [m]	17	18	18
Time of sampling fresh beachcast material [date]	2019-12-04	2019-11-08	2019-11-07
Time of sampling composted material [date]	2020-03-05	2020-03-05	2020-04-03
Temperature [°C] 50 cm depth	46.55*	26.45*	28.05*
pH (fresh beachcast material)	MD**	7.05	6.98
pH (composted material)	MD**	7.35	6.73

* Measured at the time of collection of fresh beachcast material
** Missing data

2.3 Statistical analysis

A Quade's non-parametric test was used to analyse differences in macronutrient and cadmium content in LOVA scheme analyses between different locations and seasons. This enabled using covariates (seasons when differences in chemical composition between locations were tested and vice versa) so that location could be used as a covariate when analysing the effects of seasonality on composition. Quade's test was also used to test differences in macronutrient and Cd levels between fresh beachcast data and composted beachcast data from three locations (compost site samples) using location as a covariate. To analyse differences in chemical composition in fresh beachcast and composted beachcast within the three locations, ANOVA or Welch's ANOVA were used (selected depending on homogeneity of variance tested by Levene's test). ANOVA or Welch's ANOVA was also used for testing differences in species abundance in raw beachcast. All statistical tests were performed by SPSS 28, and for the Quade's test, the R module in SPSS was used.

3 Results

The results are based on the two data sets that were used in this study - the first one being a compilation of chemical samples and analyses of fresh beachcast from harvesting locations within the LOVA scheme, and the second one consisting of chemical sampling and analyses of fresh and composted beachcast from compost sites.

3.1 Results from the LOVA scheme analyses

3.1.1 Macronutrients

The LOVA scheme analyses showed the following average chemical composition: C (17.32%), N (1.24%), P (0.17%), K (1.3 %). The magnitude of the variation is typified by the difference in NPK content between the two locations Alnäsaviken and Nisseviken, where beachcast samples from the latter location contain less than ⅕ of the N and ⅓ of P relative to the first (Figure 3, graphs a-d).

The results show significant variations in chemical composition between locations (Figure 3) and between beachcast collected during different seasons. Significant differences between locations were found using seasons as a covariate for nitrogen (N) (Quade's tests, $F(7, 27) = 4.682$, $p = 0.002$ phosphorus (P) ($F(7, 27) = 4.184$, $p = 0.003$), and C:N ratio ($F(7, 27) = 5.391$, $p < 0.001$). No significant differences between locations were found for carbon (TOC) and potassium (K).

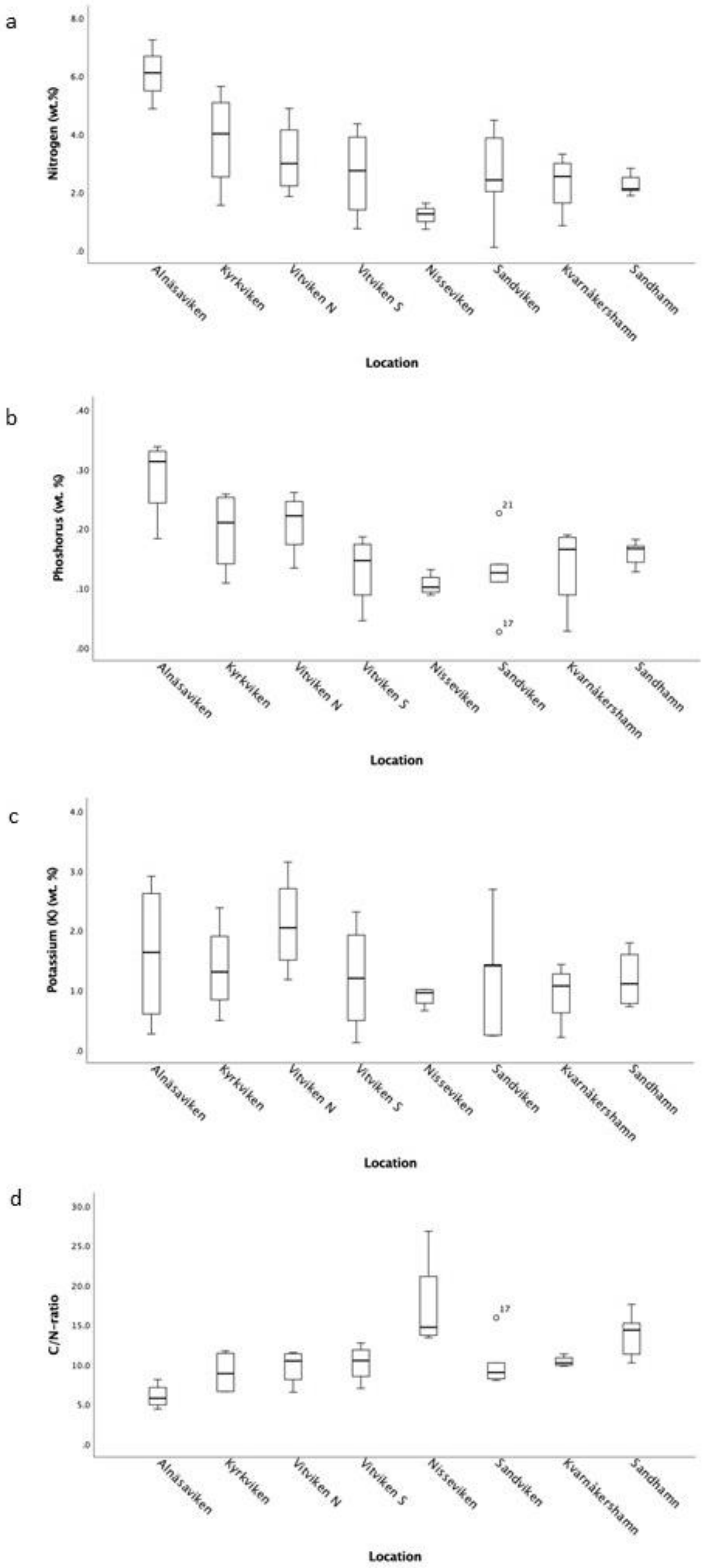
a
Nitrogen (wt.%)
8.0
6.0
4.0
2.0
.0
Alnäsaviken
Kyrkviken
Vitviken N
Vitviken S
Nisseviken
Sandviken
Kvarnåkershamn
Sandhamn
Location
b
Phoshorus (wt. %)
.40
.30
.20
.10
.00
Alnäsaviken
Kyrkviken
Vitviken N
Vitviken S
Nisseviken
Sandviken
Kvarnåkershamn
Sandhamn
Location
c
Potassium (K) (wt. %)
4.0
3.0
2.0
1.0
.0
Alnäsaviken
Kyrkviken
Vitviken N
Vitviken S
Nisseviken
Sandviken
Kvarnåkershamn
Sandhamn
Location
d
C/N-ratio
30.0
25.0
20.0
15.0
10.0
5.0
.0
Alnäsaviken
Kyrkviken
Vitviken N
Vitviken S
Nisseviken
Sandviken
Kvarnåkershamn
Sandhamn
Location

Figure 3. Overview of the LOVA scheme analyses of beachcast, showing the content of total nitrogen (N), phosphorus (P), potassium (K), and C:N by location (Alnäsaviken, Kyrkviken, Vitviken North, Vitviken South, Sandviken, Nisseviken, Kvarnåkershamn, and Sandhamn). Box-plots are showing median, quartiles, mean and max values, and outliers.

The LOVA beachcast samples in our study also show significant differences between seasons using location as a covariate for N content ($F (3, 31) = 5.783$, $p = 0.003$) (Figure 3, graph a). The mean N value was highest in the spring samples (5.6%) while in the summer samples it was only 1.5%. Significant differences were also found for the C:N ratio ($F (3, 31) = 4.028$, $p = 0.016$), where the highest ratio, which occurred in the summer samples (14.13), differed significantly from the lowest ratio which occurred in the spring samples (7.05). No significant seasonal differences between locations in respect of P, K, or C were found.

3.1.2 Cadmium

The LOVA scheme analyses contained, on average, 1.24 mg/kg DM cadmium. However, the variation in Cd levels between locations, using seasons as covariates, was significant (Quade's tests, $F (7, 27) = 2.934$, $p = 0.020$). The average values for four locations (Alnäsaviken, Kyrkviken, Sandviken and Vitviken södra) display large "within-location" variations (Figure 4).

One within-location factor is seasons, and the results show significant differences in Cd levels between seasons ($F (3, 31) = 3.66$, $p = 0.023$). The average Cd value ($F (3, 31) = 3.660$, $p = 0.023$) was highest in spring at 1.83 mg/kg DM whereas in the summer samples it was only 0.67 mg/kg DM. Although not statistically tested due to the small sample size, several locations included in this study show relatively small variations between years and between replicates (Kvarnåkershamn, Kyrkviken, Nisseviken, Sandhamn, Sandviken).

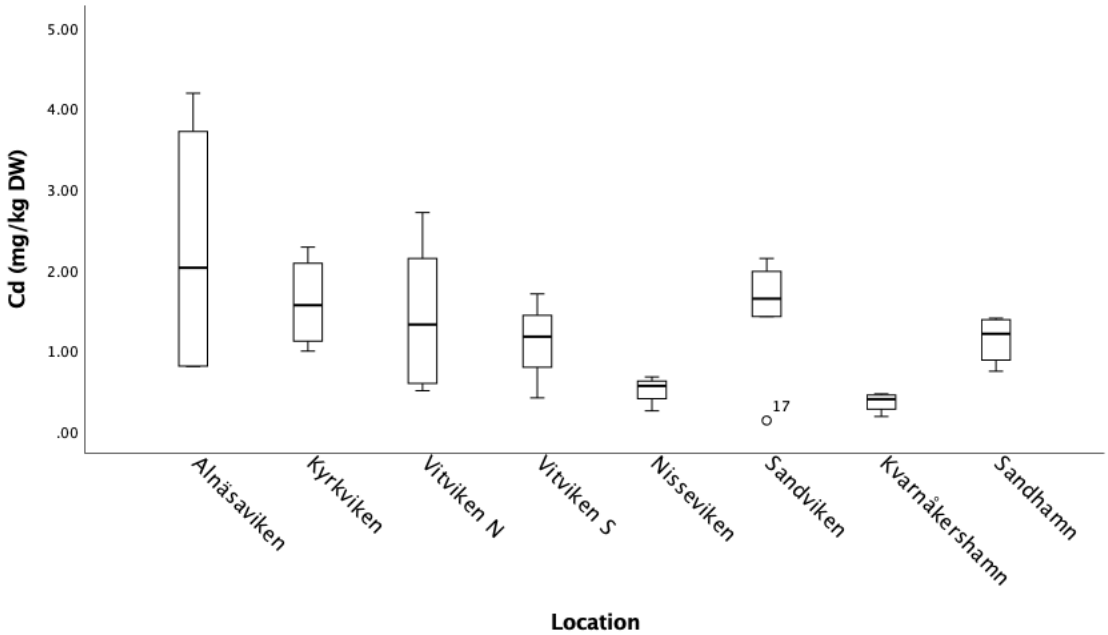

Figure 4. Overview of the LOVA scheme analyses of beachcast, showing mean value and standard deviation of the cadmium content in different locations (Alnäsaviken, Kyrkviken, Vitviken North, Vitviken South, Sandviken, Nisseviken, Kvarnåkershamn, and Sandhamn). The box-plot is showing median, quartiles, mean and max values, and outliers.

3.2 Results from the compost site samples

The species abundance of fresh beachcast material was determined during the beachcast sampling at the compost sites. In Alnäsaviken nearly half of the beachcast material was *Furcellaria lumbricalis* (estimated at 44.38%) and approximately a third was *Zostera marina* (27.38%), with the remainder comprising *Fucus vesiculosus* (16.25%), *Filamentous red algae* (9.75%) and 'other species' (2.25%). In contrast, at Lausviken nearly half of the material was *Fucus vesiculosus* (45%), again approximately a third was *Zostera marina* (29.63%), with the remainder comprising *Filamentous red algae* (5.63%) and 'other species' (19.38%) (of which the smallest amount was *Furcellaria lumbricalis* (0.5%)). At Norebod, the material mainly comprised *Furcellaria lumbricalis* (83.25%), followed by *Filamentous red algae* (14.25%), *Zostera marina* (1.25%), *Fucus vesiculosus* (0.75%), and 'other species' (0.5%). Regarding the abundance of *Furcellaria lumbricalis*, *Zostera marina*, *Fucus vesiculosus*, and 'other species', there were significant differences between the locations (but not for filamentous red algae species) (Table 1).

Table 2. Estimated species abundance (average percentage and standard deviation) of fresh beachcast material from the compost sites Alnäsaviken, Lausviken and Norebod. Results of statistical test showing significance levels (** $p < 0.01$, * $p < 0.05$) or non-significance (NS) of differences between locations (see Appendix B for complete results of statistical tests).

Location Species abundance (%)	**Alnäsaviken**	**Lausviken**	**Norebod**	Stat.test
Furcellaria lumbr.	**44.38** ± 18.64	**0.5** ± 1	**83.25** ± 12.84	**
Fucus ves.	**16.25** ± 6.29	**45** ± 18.6	**0.75** ± 0.96	**
Zostera mar.	**27.38** ± 28.38	**29.63** ± 13.92	**1.25** ± 0.5	*
Fil. red algae	**9.75** ± 9.79	**5.63** ± 9.62	**14.25** ± 11.55	NS
Other species	**2.25** ± 1.04	**19.38** ± 9.79	**0.5** ± 0.58	*

The fresh and composted beachcast show significant differences between locations (Alnäsaviken, Lausviken and Norebod) in C (TOC), N, P, and K (Table 3). The N content of fresh beachcast varied from 1.3% (Lausviken) to 5.28% (Norebod), while for composted beachcast it ranged from 1.83% (Lausviken) to 6.1% (Norebod). The P content of fresh beachcast varied from 0.15% (Norebod) to 0.29% (Alnäsaviken and Lausviken), whereas the P content in composted beachcast varied from 0.2% (Lausviken) to 0.17% (Norebod). The K content of fresh beachcast varied from 1.51% (Norebod) to 3.07% (Alnäsaviken), while the composted beachcast varied from 0.88 % (Norebod) to 1.51 % (Alnäsaviken). The C (TOC) content of composted beachcast ranged from 19 % (Lausviken) to 33.75% (Norebod).

There were significant differences in the C:N ratio between fresh and composted beachcast in Alnäsaviken (fresh 18.3, composted 8,06) and Lausviken (fresh 20.24,composted 10.81), while Norebod showed only a slight decline in C:N ratio (from 6.35 to 5.57) (Table 3). Alnäsaviken revealed high ammonium-N levels in both fresh and composted material (2432 and 3125 ppm respectively), and low nitrate-N levels for both (2.42 and 2.95 ppm respectively). In contrast, Lausviken revealed low levels of ammonium-N (145.5 and 98 ppm respectively), and a nitrate-N level increasing from fresh to composted material (2.33 ppm to 1360 ppm). Norebod displayed high ammonium levels in both the fresh and composted material (6430 and 12642 ppm respectively), combined with low nitrate levels (10.55 ppm) after three months of composting (Table 3).

For composted material, there was a significant difference in Cd content between locations but this was not the case for fresh beachcast (Table 3). However, no significant differences in "change" (fresh versus composted material) in cadmium level could be detected when using locations as covariates. For Alnäsaviken and Lausviken, the composted material had higher cadmium levels (compared to fresh beachcast), while Norebod had higher cadmium levels in fresh beachcast.

Table 3. Overview of the chemical content of beachcast from the compost sites, including Cd, C, N, ammonium, nitrate, P, K, and C:N ratio, and the NH_4^+-N to NO_3^--N ratio (presented as mean values with standard deviations) for both fresh and composed beachcast material from the compost sites, Alnäsaviken, Lausviken and Norebod. Results from statistical tests showing significance levels (** p < 0.01, * p < 0.05) or non-significance (NS) included; for complete statistical results, see Appendix C.

Location	**Alnäsaviken**		**Lausviken**		**Norebod**		**Stat. test between locations for fresh and comp.**		**Stat. test Fresh-Comp within the location**
Fresh (F) & Composted (C) beachcast **Content**	***F***	***C***	***F***	***C***	***F***	***C***	***F***	***C***	***F & C***
TOC (%)	**27.75** ± 5.12	**20.75** ± 2.63	**24.83** ± 12.84	**19** ± 3.92	**33** ± 5.35	**33.75** ± 1.26	NS	**	*
N (%)	**1.58** ± 0.34	**2.75** ± 0.7	**1.3** ± 0.22	**1.83** ± 0.35	**5.28** ± 0.92	**6.1** ± 0.54	**	**	**
C:N (TOC/N %)	**18.3** ± 5.2	**8.06** ± 2,79	**20.24** ± 11.59	**10.81** ± 3.24	**6.35** ± 1.27	**5.57** ± 0.55	*	*	**
Ammonium-N NH_4^+-N (ppm)	**2432** ± 1493	**3125** ± 544	**145.5** ± 204	**98** ± 51	**6430** ± 1072	**12642** ± 4887	**	**	NS
Nitrate-N NO_3^--N (ppm)	**2.42** ± 0.34	**2.95** ± 0.29	**2.33** ± 0,29	**1360** ± 539	**6.7** ± 0	**10.55** ± 3.48	**	**	*
P (%)	**0.29** ± 0.11	**0.13** ± 0.02	**0.29** ± 0.02	**0.2** ± 0.05	**0.15** ± 0.02	**0.17** ± 0.02	**	*	**
K (%)	**3.07** ± 0.16	**1.51** ± 0.1	**2.94** ± 0.55	**0.99** ± 0.2	**1.57** ± 0.27	**0.88** ± 0.24	**	**	**
Maturity index (NH_4^+-N/ NO_3^--N)	**1037** ± 747	**1075** ± 258	**62.84** ± 88.91	**0.08** ± 0.04	**960** ± 160	**1408** ± 889	*	**	NS
Cd (mg/kg DM)	**0.80** ± 0.19	**1.05** ± 0.17	**0.94** ± 0.26	**1.38** ± 0.26	**1.15** ± 0.19	**0.85** ± 0.22	NS	*	NS

** Significant (p < 0.01); * Significant (p < 0.05); NS (not significant)

4 Discussion

The results from the LOVA scheme analyses and compost site samples showed that the macronutrients content is close to the ranges found in earlier studies of beachcast from the Baltic Sea Region, (Franzén et al., 2019; Michalak et al., 2017; Vincevica-Gaile et al., 2022). However, the N content (Figure 3) was somewhat lower in relation to beachcast nitrogen found in earlier studies and, for comparison, lower compared to other manures: cattle: 3.45%, pig: 4.45%, poultry: 6.93% as measured in the dry matter of fresh manure material (Kirchmann & Witter, 1992). The K level was slightly higher than K levels found in earlier studies of Baltic Sea beachcast and approximately the same level as that measured in fresh manure, 0.73-1.85 % (Kirchmann & Witter, 1992). A substantially lower P content in beachcast compared to manures is also consistent with other beachcast studies (Franzén et al., 2019; Michalak et al., 2017; Vincevica-Gaile et al., 2022).

The findings that for one location the N content is approximately ⅕ of the N content of the other and the P content approximately ⅓ of the P content of the other typify the magnitude of the local variation in macronutrient content, while seasonal variations are typified by an average N value in spring samples of 5.6%, compared to a summer sample value of 1.5%. These variations on a regional scale between locations and seasons make both the raw and composted material unpredictable for use. The generally low P value of biofertilisers reduces their usefulness in an intensive agricultural system that requires high nutrient density (Dahiya et al., 2018). Likewise, with intensive agricultural practices requiring high precision, nutrient fluctuations have become a barrier to the general use of biofertilisers by farmers (Case et al., 2017). Similarly, resource substitution using beachcast is challenging.

The C:N ratios for beachcast in this study also vary: LOVA scheme analyses vary from just below 5 to 25 (Figure 3). The C:N ratios of fresh beachcast found in this study vary between approximately 6 and 20, whereas values for composted material varied between 6 and 10 (Table 3). A local difference in C:N ratios proved significant for both fresh and composted beachcast from the LOVA scheme analyses (Figure 3) and the compost site samples (Table 3). A lower C:N ratio in composted material is expected due to decomposition of biomaterial and release of nitrate in the nitrification process when ammonium is also formed (Cáceres et al., 2018), which is also the case in the chemical site samples when comparing fresh and composted material (Figure 3 and Table 3).

Ammonium-nitrate ratios at Alnäsaviken and Norebod measuring in the thousands (Table 3), indicate that the composts are far from mature (maybe also phytotoxic), while Lausviken displayed an index of approximately zero (Table 3) during the same period, indicating a mature and non-phytotoxic material. The hugely varying maturity indices (i.e. ammonium and nitrate ratios) of the fresh and composted samples (Table 3) also indicate that the "behaviour" of beachcast during decomposition is highly unpredictable. To produce a useful compost, the typically low C:N ratio of fresh beachcast (i.e. macroalgae), could be considered a "weak" link, as it increases the risk of N loss through ammonia and nitrous gas emissions (Han et al., 2014).

Among the above-mentioned challenges, however, the Cd contamination risk is the limiting factor if beachcast is to be used at all. The LOVA scheme analyses contained, on average, 1.24 mg/kg DM cadmium (Figure 4), which is within or close to the ranges found in earlier studies of beachcast from the Baltic Sea Region at 0.71-1.41 mg/kg DM (Franzén et al., 2019; Michalak et al., 2016, 2017; Vincevica-Gaile et al., 2022). Although the average Cd level of the LOVA scheme analyses, as well as fresh and composted beachcast (Table 3), were below the EU threshold for biofertilisers at 1.5 mg Cd kg^{-1} DM, there are single samples that exceed the level (Figure 4), which causes uncertainty regarding its use. The results for composted beachcast showed significant differences in Cd content between locations, unlike fresh beachcast that showed no significant variation. It was also found that some locations are associated with a considerable "within-location" variation (based on samples from various years) (Figure 4). This adds to the unpredictability and further complicates management decisions regarding its use, and calls for frequent and continuous sampling of the material to map the Cd levels in the region.

During composting, accumulation of Cd might be expected due to the concentration increasing with the decomposition of the biomass (Greger et al., 2007). However, no significant differences between fresh and composted beachcast material were detected in the compost samples. A deviation in the form of no Cd concentration during composting of beachcast material has also occurred in other studies, without the cause being identified (Greger et al., 2007; Michalak et al., 2017). The fate of Cd (e.g. leakage and accumulation) may depend on several factors, such as pH, carbon content and transfer factors (Hanc et al., 2009), and the need to predict the risk of Cd accumulation in soil and Cd crop contamination from beachcast application in agriculture under practical conditions is highly important, e.g. field experiments that reflect the practical use of beachcast.

This study presents the regional variations in the species abundance of beachcast (Table 2). Other studies have shown that species abundance varies with season and location (Gubelit, 2022; Paar et al., 2021), and confirmed a connection between species and macronutrient composition (Michalak et al., 2017) and Cd content (Franzén et al., 2019). This combination pinpoints how problematic the task of predicting the chemical content of beachcast really is, and consequently for controlling the composting process. However, knowledge of the local species variations in the region could potentially contribute to advancing the composting treatment practices of beachcast.

Perhaps the ability to predict fluctuations in chemical content could be improved by better mapping the macronutrient and Cd content variations within the current policy scheme. In sampling for natural resource monitoring, any prior information on variation should be optimally utilised to find an efficient sampling design to improve management schemes (de Gruijter et al., 2006). A practical measure that could be taken based on the LOVA scheme results is to sort "batches", so the batches that exceed legislative Cd thresholds (e.g. the EU limit for bio-based fertilisers at 1.5 mg Cd kg^{-1} DM) are treated separately from the ones that could be safely used in agriculture. By also extending the sampling to include not only fresh but composted material and documenting the time of composting, the C:N ratio, as well as the ammonium-nitrate ratio (i.e. maturity index), could be calculated at the beginning and at the end of the process, and be related to the composting time. Additionally, including a simple form of documentation of macrophyte species groups, i.e. their distribution in the samples, could deepen the knowledge of the usefulness of various species groups in agriculture (and thereby the suitability of beachcast as a biofertiliser). Use of past experimental knowledge could be a complementary and pragmatic method because historical documentation sometimes refers to different types of species by names that disclose their suitability as fertilisers (Säve, 1938). In this way, knowledge of the composting process and the "behaviour" of the material could be increased and assist in a waste-to-resource conversion of beachcast. Financially, supporting experimentation with co-composting using locally available biowaste could generate a more suitable product for agricultural use by engineering a fertiliser in which the chemical properties could be controlled.

Essentially, experimentation should be coupled with dissemination and discussion of the findings with farmers to increase the usefulness of the findings. The response could serve to guide a potential (re-)introducing beachcast as a resource and developing theoretically promising and practically anchored treatment procedures.

5 Conclusions

The primary analytical data of beachcast provided by this study shows significant variations in macronutrient and cadmium content of the material on a regional scale. This previously unknown information has served as input for discussing adjustments to sampling design within the current policy scheme, to provide knowledge for improving beachcast management in the sense of making it useful in a circular economy context. Data collection could be facilitated by extending the LOVA scheme sampling to include (1) additional sampling post-composting and documentation of the composting time, (2) calculating C:N ratio and maturity index (ammonium-nitrate ratio), and (3) continuous documentation of the Cd content for each harvesting location, and (4) supporting experimentation with co-composting using locally available biowaste to engineer a fertiliser (i.e. to enable control of the chemical properties). Moreover, collecting historical data on treatments, such as the treatment duration, references to different types of species by name that would help to indicate their suitability as fertilisers, could support experimentation with treatment. This data and knowledge could eventually assist policy in supporting context-specific treatment strategies that could bolster the waste-to-resource conversion of beachcast in the optimum manner seen from a systems perspective.

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Appendix A. Instructions for beachcast sampling within the LOVA scheme

Translation (from Swedish):

Collect fresh beachcast material from 3-5 spots on the beach at the same time as the harvesting is taking place, and mix the material in a bucket. It is important to obtain a representative mix of species.

If there is only one species to sample on the occasion, this should be noted as a remark in the marking of the sample. Take at least 500 grams of beachcast from the bucket and place it in a plastic jar with a screw-top or similar. Mark the jar with the sampling place and dates, and please take a photo of the sampling place. Also, place a note with the same information written in pencil in the jar (in case the marking disappears). Sampling should be conducted at least one time, a maximum of two times a year.

Original text (Swedish):

"Samla in färskt material från 3-5 platser på stranden i samband med skördetillfället och blanda i en hink. Det är viktigt att se till att få med en representativ blandning av olika arter.
Om det bara finns en art att ta prov på vid provtagningstillfället så ska detta noteras som anmärkning i märkningen av provet. Ta minst 500 gram släke från hinken och lägg i en plastburk med skruvlock eller liknande. Märk burken med provtagningsplats och datum och ta gärna ett foto på provtagningsplatsen. Lägg också i en lapp med samma uppgifter skrivet med blyerts i burken (som säkerhet i fall annan märkning försvinner). Provtagning ska göras minst 1 ggr och maximalt 2 ggr per år."

Appendix B. Statistical analyses of species abundance

Table 1B. Statistical analyses of species abundance for the results presented in Table 2.

Species or Species Group	**Fresh Beachcast – Locations** Test: ANOVA/ Welch ANOVA
Furcellaria lumbricalis	F (2, 9) = 31.71, p < 0.001
Fucus vesiculosus	Welchs' F (2; 4.37) = 18.02, p = 0.008
Zostera marina	Welchs' F (2; 4.06) = 31.71 p = 0.036
Filamentous Red Algae	F (2, 9) = 1.03, p = 0.397
Other species (lumped group)	Welchs' F (2; 5.34)= 7.93 p = 0.025

Appendix C. Statistical analyses of fresh and composted beachcast

Table 1C. Statistical analyses of for the results presented in Table 3, fresh as well as composted beachcast in relation to location, and composted versus fresh beachcast.

Element	Fresh Beachcast - Locations ANOVA/Welch ANOVA	Composted Beachcast Locations ANOVA/Welch ANOVA	Composted vs Fresh Beachcast Quade's test
TOC	$F\ (2, 9) = 0.94$ $p = 0.427$	$F\ (2, 9) = 32.7$ $p < 0.01$	$F(1, 22) = 6.83$ $p = 0.016$
N	$F_w\ (2, 5.17) = 31.3$, $p = 0.001$	$F_w\ (2, 4.03) = 63.9$ $p < 0.01$	$F(1, 22) = 16.32$ $p = 0.001$
P	$F\ (2, 9) = 5.5$ $p < 0.027$	$F\ (2, 9) = 4.58$ $p = 0.043$	$F(1, 22) = 8.53$ $p = 0.008$
K	$F\ (2, 9) = 20.98$ $p < 0.01$	$F\ (2, 9) = 12.52$ $p = 0.003$	$F(1, 22) = 46.98$ $p = 0.0001$
C/N	$F_w\ (2, 4.27) = 10.87$ $p = 0.021$	$F\ (2, 9) = 55.1$ $p = 0.045$	$F(1, 22) = 8.39$ $p = 0.008$
NH4	$F\ (2, 9) = 35.5$ $p < 0.01$	$F_w\ (2, 4.04) = 63.9$ $p < 0.01$	$F(1, 22) = 3.28$ $p = 0.084$
NO3	$F\ (2, 9) = 377.4$ $p < 0.01$ *	$F_w\ (2, 4.03) = 63.9$ $p < 0.01$	$F(1, 22) = 14.55$ $p = 0.001$
NH4/NO3	$F\ (2, 9) = 5.96$ $p < 0.023$	$F_w\ (2, 4.0) = 33.987$ $p = 0.003$	$F(1, 22) = 0$ $p = 1.00$
Cd	$F\ (2, 9) = 2.54$ $p < 0.134$	$F\ (2, 9) = 5.91$ $p = 0.023$	$F(1, 22) = 0.79$ $p = 0.383$

* ANOVA test performed although equal homogeneity not was met according to Levene's test. (Welch's test was not possible due to lack of variance in one group).

F_w = Welch's F