Blue biomass composting technology

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SAMMENDRAG:

Denne rapporten presenterer metodene og resultatene fra innledende forsøk på kompostering av marine restråstoff i regi av MARIGREEN, et prosjekt finansiert av ERA-NET BlueBio cofund-programmet. Hovedmålet med MARIGREEN er å oppgradere dårlig utnyttet restråstoff fra blå verdikjeder (fisk, skjell, alger) for å bruke dem som gjødsel og biostimulanter i økologisk dyrking. Prosjektet ledes av UPB (Romania) og er i samarbeid med USAMV (Romania), AUTh (Hellas), DTU (Danmark), UCPH (Danmark), NORCE (Norge) og industripartnerne Alumichem AS (Danmark), Norgeskjell AS (Norge), Sigurd Folland AS (Norge), Fjordlaks AS (Norge) og Algea AS (Norge).

Kompostforsøkene ble gjort på tre ulike nivå: småskala (2 liter) i såkalte Dewar-flasker; mellomskala (140 liter) med en Jordakompost® isolert komposttrommel; og storskala (ca. 7 m3) med rankekompostering. De første forsøkene i Dewar-flaskene var basert på kjente råvarer som hestemøkk, flis og halm og hadde til hensikt å bli kjent med utstyret og metoden, som kalles for en selvoppvarmings-test. Denne testen brukes som regel til å estimere modenhet og stabilitet i ferdig kompost, men her ønsket vi å se på varmeutvikling i ferskt materiale. Forsøkene med kjente råvarer ble etterfulgt av forsøk med de marine restråstoffene stortare, to typer algefiber fra prosessering av grisetang, oppmalte fiskebein fra hydrolyserte torskehoder, og tørket fiskemel av

hvitfisk. Disse materialene har, så vidt vi vet, hittil ikke blitt testet i Dewar-flasker. Som et alternativt strukturmateriale i Dewar-flaskene og i komposttrommelen eksperimenterte vi med ekspanderte leireaggregater (Leca®).

Forsøket med hestemøkk bekreftet at Dewar-flaskene kan brukes til å estimere potensialet for varmgang i ferskt materiale. De marine restråstoffene utviklet også varme, i flere tilfeller over 45 °C (som er grensen for å være termofilt) og i noen tilfeller opp til 60 °C, inkludert algefiber alene med Leca®. Blandingen med algefiber og Leca® ble brukt til å lage kompost i komposttrommelen, men på denne skalaen gikk aldri temperaturen over 30 °C. Dette kan skyldes at det var kaldt på rommet i starten (under 5 °C), at trommelen avga for mye varme, at det var for lite lettilgjengelig nitrogen eller karbon, eller at forholdet mellom algefiber og Leca® var feil.

På storskalanivå bygde vi en kompostranke med en blanding av algefiber, talle fra storfe, flis fra bartrær, og sediment fra ensilert, oppkvernet restråstoff av hvitfisk, som inneholdt vesentlig fiskebein. Denne blandingen ga varmgang med temperaturer over 60 °C i korte perioder.

Det kom mange nyttige erfaringer ut av disse innledende forsøkene, som blir brukt til planlegging av videre forsøk med marine restråstoff. Dewar-flaskene egner seg til å estimere potensialet til kompostbarhet av ferske materialer, men de har sine begrensninger. Dynamikken i en kompostblanding blir annerledes når volumet økes fra 2 liter til flere kubikk. Og flaskene kan ikke brukes til å produsere «ferdig» kompost, som er avhengig av å være kontakt med et mangfold av organismer over lang tid. Forsøkene bekrefter at marine restråstoff egner seg som råvarer i kompost, både i kombinasjon med kjente materialer som hestemøkk og flis, men også alene (med Leca®). Leca®-kulene, som ikke inneholder karbon eller nitrogen, fungerer godt som strukturmaterial.

Summary:

This report presents the methods and results from preliminary trials with composting marine residual raw materials under the auspices of MARIGREEN, a project funded by the ERA-NET BlueBio cofund program. The main goal of MARIGREEN is to upgrade poorly utilized residual raw materials from blue value chains (fish, shells, algae) for use as fertilizer and biostimulants in organic farming. The project is led by UPB (Romania) and is in collaboration with USAMV (Romania), AUTh (Greece), DTU (Denmark), UCPH (Denmark), NORCE (Norway), and the industrial partners Alumichem AS (Denmark), Norgeskjell AS (Norway), Sigurd Folland AS (Norway), Fjordlaks AS (Norway), and Algea AS (Norway).

The compost experiments were carried out at three different levels: small-scale (2 litres) in so-called Dewar flasks; medium-scale (140 liters) with a Jordakompost® insulated compost drum; and large-scale (approx. 7 m3) with windrow composting. The first experiments in the Dewar flasks were based on known raw materials such as horse dung, sawdust, and straw and were intended to familiarize ourselves with the equipment and the method, which is called a self-heating test. This test is usually used to estimate the maturity and stability of finished compost, but here we wanted to look at heat development in fresh material. The trials with the familiar raw materials were followed by trials with the marine residual raw materials, tangle kelp, two types of algae fiber from processing rockweed (brown seaweed), ground fish bones from hydrolyzed cod heads, and dried fish meal from fish in the cod family. These materials have, to our knowledge, not yet been tested in Dewar flasks. As an alternative bulking material in the Dewar bottles and in the compost drum, we experimented with expanded clay aggregates (Leca®).

The experiment with horse dung confirmed that the Dewar flasks can be used to estimate the potential for heat generation in fresh material. The marine residual raw materials also developed heat, in several cases above 45 °C (which is the lower limit for being thermophilic) and in some cases up to 60 °C, including algae fiber alone with Leca®. The mixture with algae fiber and Leca® was used to make compost in the compost drum, but on this scale, the temperature never exceeded 30 °C. This may be due to the fact that the room was cold at the start (below 5 °C), that the drum gave off too much heat, that there was too little easily available nitrogen or carbon, or that the ratio between algae fiber and Leca® was incorrect.

On a large-scale level, we built a compost windrow with a mixture of algae fiber, bedding from cattle, wood chips from conifers, and sediment from acidified, ground-up residues from codfish, which contained substantial bones. This mixture gave rise to temperatures above 60 °C for short periods.

Many useful experiences came out of these initial experiments, which are being used to plan further experiments with marine residues. The Dewar flasks are suitable for estimating the potential compostability of fresh materials, but they have their limitations. The dynamics of a compost mixture change when the volume is increased from 2 liters to several cubic meters. And the bottles cannot be used to produce "finished" compost, which depends on being in contact with a variety of organisms over a long period of time. The experiments confirm that marine residues are suitable as raw materials in compost, both in combination with familiar materials such as horse dung and wood chips, but also alone (with Leca®). The Leca® aggregates, which do not contain carbon or nitrogen, work well as a structural material.

Περίληψη:

Η παρούσα έκθεση παρουσιάζει τις μεθόδους και τα αποτελέσματα προκαταρκτικών δοκιμών με κομποστοποίηση θαλάσσιων υπολειμματικών πρώτων υλών υπό την αιγίδα του MARIGREEN, ενός έργου που χρηματοδοτείται από το πρόγραμμα συγχρηματοδότησης ERA-NET BlueBio. Ο κύριος στόχος της έρευνας MARIGREEN είναι η αναβάθμιση των ανεπαρκώς χρησιμοποιούμενων υπολειμματικών πρώτων υλών από μπλε αλυσίδες αξίας (ψάρια, κοχύλια, φύκια) για χρήση ως λίπασμα και βιοδιεγερτικά στη βιολογική γεωργία. Το έργο διευθύνεται από το Πανεπιστήμιο UPB (Ρουμανία) και υλοποιείται σε συνεργασία με τα Πανεπιστήμια USAMV (Ρουμανία), ΑΠΘ (Ελλάδα), DTU (Δανία), UCPH (Δανία), NORCE (Νορβηγία), και τους βιομηχανικούς εταίρους Alumichem AS (Δανία), Norgeskjell AS (Νορβηγία), Sigurd Folland AS (Νορβηγία), Fjordlaks AS (Νορβηγία), και Algea AS (Νορβηγία).

Τα πειράματα κομποστοποίησης πραγματοποιήθηκαν σε τρία διαφορετικά επίπεδα: μικρής κλίμακας (2 λίτρα) σε φιάλες Dewar, μεσαίας κλίμακας (140 λίτρα) με μονωμένο δοχείο

κομποστοποίησης Jordakompost®, και μεγάλης κλίμακας (περίπου 7 m3) με κομποστοποίηση σειριακής διάταξης. Τα πρώτα πειράματα σε φιάλες Dewar βασίστηκαν σε γνωστές πρώτες ύλες, όπως κοπριά αλόγων, πριονίδι και άχυρο, και είχαν ως σκοπό την εξοικείωση με τον εξοπλισμό και τη μέθοδο, η οποία ονομάζεται δοκιμή αυτοθέρμανσης. Αυτή η δοκιμή χρησιμοποιείται συνήθως για την εκτίμηση της ωριμότητας και της σταθερότητας της τελικής κομπόστας, αλλά εδώ θέλαμε να εξετάσουμε την ανάπτυξη θερμότητας σε φρέσκο υλικό. Τις δοκιμές με τις γνωστές πρώτες ύλες ακολούθησαν δοκιμές με τις θαλάσσιες υπολειμματικές πρώτες ύλες, τα φύκια, δύο τύπους ινών φυκιών από την επεξεργασία ζιζανίων (καφέ φύκια), αλεσμένα οστά ψαριών από υδρολυμένα κεφάλια μπακαλιάρου και αποξηραμένα ιχθυάλευρα από ψάρια της οικογένειας μπακαλιάρου. Αυτά τα υλικά, εξ όσων γνωρίζουμε, δεν έχουν ακόμη εξετασθεί σε φιάλες Dewar. Ως εναλλακτικό διογκωτικό υλικό στις φιάλες Dewar και στο δοχείο κομποστοποίησης, χρησιμοποιήθηκε πειραματικά αδρανής διογκωμένη άργιλος (Leca®).

Το πείραμα με κοπριά αλόγων επιβεβαίωσε ότι οι φιάλες Dewar μπορούν να χρησιμοποιηθούν για την εκτίμηση της δυνατότητας παραγωγής θερμότητας σε φρέσκο υλικό. Οι θαλάσσιες υπολειμματικές πρώτες ύλες ανέπτυξαν επίσης θερμότητα, σε αρκετές περιπτώσεις πάνω από 45 °C (που είναι το κατώτερο όριο για να είναι θερμόφιλες) και σε ορισμένες περιπτώσεις έως και 60 °C, συμπεριλαμβανομένων των ινών φυκιών (από μόνες τους) με Leca®. Το μίγμα με ίνες φυκιών και Leca® χρησιμοποιήθηκε για την παρασκευή κομπόστας στο δοχείο κομποστοποίησης, αλλά σε αυτή την κλίμακα, η θερμοκρασία δεν ξεπέρασε ποτέ τους 30 °C. Αυτό μπορεί να οφείλεται στο γεγονός ότι το δωμάτιο ήταν κρύο στην αρχή (κάτω από 5 °C), ότι το δοχείο (αντιδραστήρας) εξέπεμπε υπερβολική θερμότητα, ότι υπήρχε πολύ λίγο άμεσα διαθέσιμο άζωτο ή άνθρακας, ή ότι η αναλογία μεταξύ ινών φυκιών και Leca® δεν ήταν σωστή.

Σε μεγάλη κλίμακα, κατασκευάσαμε σειριακή διάταξη κομποστοποίησης με μίγμα ινών φυκιών, στρωμνή από βοοειδή, ροκανίδια από κωνοφόρα, και ιζήματα από οξινισμένα, αλεσμένα υπολείμματα από μπακαλιάρο, τα οποία περιείχαν σημαντική ποσότητα οστών. Αυτό το μίγμα οδήγησε σε θερμοκρασίες πάνω από 60 °C για μικρά χρονικά διαστήματα.

Προέκυψαν πολλές χρήσιμες εμπειρίες από αυτά τα αρχικά πειράματα, τα οποία χρησιμοποιούνται για τον προγραμματισμό περαιτέρω πειραμάτων με θαλάσσια υπολείμματα. Οι φιάλες Dewar είναι κατάλληλες για την εκτίμηση της πιθανής κομποστοποίησης φρέσκων υλικών, αλλά έχουν τους περιορισμούς τους. Η δυναμική ενός μίγματος κομποστοποίησης αλλάζει όταν ο όγκος αυξάνεται από 2 λίτρα σε αρκετά κυβικά μέτρα. Από την άλλη πλευρά, οι φιάλες δεν μπορούν να χρησιμοποιηθούν για την παραγωγή «τελικής» κομπόστας, η οποία εξαρτάται από την επαφή με διάφορους οργανισμούς για μεγάλο χρονικό διάστημα. Τα πειράματα επιβεβαιώνουν ότι τα θαλάσσια υπολείμματα είναι κατάλληλα ως πρώτες ύλες στην κομποστοποίηση, τόσο σε συνδυασμό με γνωστά υλικά, όπως κοπριά αλόγων και ροκανίδια, όσο και από μόνα τους (με το Leca®). Τα μίγματα Leca®, τα οποία δεν περιέχουν άνθρακα ή άζωτο, λειτουργούν καλά ως δομικό υλικό.

Rezumat:

Acest raport prezintă metodele și rezultatele încercărilor preliminare privind compostarea materiilor prime reziduale marine sub auspiciile MARIGREEN, un proiect finanțat prin programul de programul ERA-NET BlueBio Cofund.

Scopul principal al proiectului MARIGREEN este de a valorifica materiile prime reziduale din lanțurile valorice de acvacultură și pescuit (pești, scoici, alge) pentru a fi utilizate ca îngrășăminte și biostimulatori în agricultura ecologică. Proiectul este condus de UPB (România) și si are ca parteneri științifici NORSOK? USAMV (România), AUTh (Grecia), DTU (Danemarca), UCPH (Danemarca), NORCE (Norvegia) și partenerii industriali Alumichem AS (Danemarca), Norgeskjell AS (Norvegia), Sigurd Folland AS (Norvegia), Fjordlaks AS (Norvegia) și Algea AS (Norvegia).

Experimentele pentru obținerea compostului au fost efectuate la trei niveluri diferite: la scară mică (2 litri) în recipientele Dewar; la scară medie (140 litri) cu un tambur izolat pentru compost Jordakompost®, și pe scară largă (aprox. 7 m^3) cu compostare în andană. Primele experimente din recipienții Dewar s-au bazat pe materii prime cunoscute, cum ar fi balega de cal, rumeguș și paie și au avut ca scop familiarizarea cercetătorilor cu echipamentul și metoda numită test de autoîncălzire. Acest test este folosit de obicei pentru a estima maturitatea și stabilitatea compostului finit, dar în acest caz ne-a interesat dezvoltarea căldurii în materialul proaspăt.

Încercările cu materiile prime cunoscute au fost urmate de încercări cu materiile prime marine reziduale: varecul, două tipuri de fibre de alge din procesarea alge de rocă (alge marine brune), oase de pește măcinate obținute din capete de cod hidrolizat și făină de pește uscată din pește din familia codului. Din cunoștințele noastre, aceste materiale nu au fost încă testate în recipiente Dewar. Ca material alternativ de încărcare în sticlele Dewar și în tamburul de compost, am experimentat cu agregate de argilă expandată (Leca®).

Experimentul cu bălegar de cal a confirmat că recipientele Dewar pot fi folosite pentru a estima potențialul de generare de căldură în materialul proaspăt. Materiile prime marine reziduale au dezvoltat căldură, în câteva cazuri peste 45 °C (care este limita inferioară pentru composturile termofile) și în unele cazuri până la 60 °C, inclusiv fibrele de alge amestecate numai cu Leca®. Amestecul ce conține fibre de alge și Leca® a fost folosit pentru a face compost în tamburul de compost, dar la această scară, temperatura nu a depășit niciodată 30 °C. Acest lucru se poate datora faptului că încăperea era rece la început (sub 5 °C), că tamburul degaja prea multă căldură, că era prea puțin azot sau carbon ușor accesibil sau că raportul dintre fibrele de alge și Leca® a fost incorect.

La o scară largă, am construit o grămadă de compost cu un amestec de fibre de alge, așternut de la vite, așchii de lemn de la conifere și sedimente din reziduuri acidulat și măcinate de cod, cu un conținut substanțial de oase. Acest amestec a dat naștere la temperaturi peste 60 °C pentru perioade scurte.

Multe experiențe utile au rezultat din aceste experimente inițiale, care sunt folosite pentru a planifica experimente ulterioare cu reziduuri marine. Recipientele Dewar sunt potrivite pentru estimarea potențialului compostabil al materialelor proaspete, dar au limitările lor. Dinamica unui amestec pentru compost se schimbă atunci când volumul crește de la 2 litri la câțiva metri cubi. Iar recipientele nu pot fi folosite pentru a produce compost „finisat”, care depinde de contactul cu o varietate de organisme pe o perioadă lungă de timp. Experimentele confirmă faptul că reziduurile marine sunt potrivite ca materie primă în compost, atât în combinație cu materiale familiare precum bălegar de cal și așchii de lemn, dar și singure (cu Leca®). Agregatele Leca®, care nu conțin carbon sau azot, funcționează bine ca material structural.

COUNTRY:	Norway
COUNTY:	Møre og Romsdal
MUNICIPALITY:	Tingvoll

APPROVED	**PROJECT LEADER**
Turid Strøm	Anne-Kristin Løe
NAME	**NAME**

Preface

This report is the first deliverable produced by NORSØK in the project "Sustainable utilization of MARine resources to foster GREEN plant production in Europe" (MARIGREEN). This project is funded by the ERA-net BlueBioCofund and is a collaboration between research and industry partners from Romania, Greece, Denmark, and Norway.

Composting is a well-established practice in organic farming, closely linked to the concepts of soil health and on-farm nutrient cycling. Composting can also be applied to handle organic waste, and possibly facilitate the use of such waste in agriculture. Compost may be applied directly as a soil amendment but can also be used for the production of compost extracts ("compost tea"). Such extract may have bio-stimulating effects which can be beneficial for plant production, e.g., to cope with environmental stresses such as drought or cold spells.

While composting is something very many people practice, is it a complicated process to study and monitor. Many conditions affect the initiation and duration of self-heating, which is the first step in a thermophilic, aerobic decomposition of organic materials – also called composting. Thanks to MARIGREEN, NORSØK staff has been able to expand their competence and equipment for conducting trials with composting. The composts will be subject to further testing by the project partners, especially in Romania and Greece. This report describes initial trials with composting of marine-derived residual organic materials which were conducted at NORSØK during 2022-2023, highlighting results and experiences we made that may be of interest to other compost researchers.

Tingvoll, 03.07.23

Anne-Kristin Løes, leader of MARIGREEN WP3 (Soil and fertilizers)

Table of content

1 Background

1.1 Bioeconomy and the use of waste materials for fertilization

Conducting research along the value chain, and upcycling of “waste” to create valuable new products, have been keywords for scientific studies in Norway over the last decade. Residual organic materials such as composted garden waste, seaweeds and animal by-products have been of high interest in organic farming since this production method was defined and regulated by IFOAM in 1982 (Schmid 2007). With an increasing volume of organic production, the need for such materials increases, and it increases even more because many organic farmers want to phase out the use of plant nutrients and organic matter derived from conventional plant and animal production. This may be motivated by a demand to protect and increase the integrity and independence of organic farming, but also by a need to avoid the transfer of toxic compounds such as pesticide residues.

The Norwegian food system has a very large blue sector where significant amounts of fish and other seafood are produced for domestic consumption and export, and a much smaller green sector which covers less than 50% of the national annual food intake for a population of about 5 million people. Traditionally, there has not been much collaboration between these sectors in research and development activities, but such collaboration has been seen as beneficial in the national bioeconomy strategy. The Norwegian Centre for Organic Agriculture (NORSØK) is located on the north-western coast of southern Norway and is hence in a geographically good position to participate in blue-green collaboration projects. One of these is the ERA-net project *“Sustainable utilization of MARIne resources to foster GREEN plant production in Europe”* (MARIGREEN, 2021-2024), funded by the Blue Bio Cofund.

Several industry partners from Norway are active in the project, delivering materials which are tested as fertilizers or as substrates for compost. Algea AS in Kristiansund has delivered residues of seaweed material. Fjordlaks AS in Ålesund and Brødrene Folland AS in Averøy have delivered residual materials after processing of white fish (cod, saithe etc.) for clip fish. The residual materials tested in MARIGREEN currently have no commercial value and are treated as waste, or there is a need for better utilization. The materials are further described in Material and methods.

One main topic of NORSØK in the MARIGREEN project is to study humification of organic materials via composting of marine materials. A scientifically controlled and described composting of marine materials (only) has not been performed under Norwegian conditions until now. Hence, several initial trials were required to establish enough knowledge and practical experience to initiate a factorial experimental design. The aim of the present report is to present these initial trials, how they were conducted and what we learned from conducting them, while the factorial experiment will be published separately.

1.2 Composting as a process to improve material quality

Composting of organic materials is widely recognized as a method to reduce the risk of spreading pathogens and propagation materials from weeds. Further benefits of this technology are a significant mass reduction, due to gaseous losses of carbon (C) and other elements; stabilization of organic matter; and easier handling and spreading in field. Composting of seaweed has been tested e.g., by Illera-Vives et al. (2013). They found that seaweed material alone had a carbon to nitrogen (CN) ratio of about 17, which is below the optimal level for a thermophilic composting process where the CN ratio should be 25-30. The seaweed material was a mixture of *Laminaria* and *Cystoseira* brown macroalgae which drifted onto the shores of Galicia, Spain. 20% (by volume) of seaweed material, with a dry matter content of 17%, was mixed with 20% of fish residual material from horse mackerel (heads, spines, and skin) and 60% of pine bark. Layers of these materials were arranged in conic heaps sized 6 x 2 x 1.5 m^3, which were covered with geotextile. The heaps were turned weekly over 6 weeks and thereafter each 2nd week until 10 weeks of composting in total, whereafter several characteristics were measured. Self-heating was rapidly initiated, and temperatures reached 70 °C after 10 days. The thermophilic phase, with temperatures above 50 °C, lasted for about 40 days. The resulting compost possessed many valuable characteristics, but the salt content of the fish waste was quite high. Hence, the content of sodium in the compost (1% of DM) was higher than the content of calcium (0.8%) and potassium (0.7%). The authors propose that this can be reduced by rinsing of the fish waste in fresh water.

In our case, the starting point for making a compost was seaweed residuals from chemical processing of rockweed (*Ascophyllum nodosum*). After extraction of dried and ground rockweed, which is harvested along the Norwegian coast, the remaining material is called “algae fiber”. The material is a black paste with a dry matter content of 25-30%, a pH around 9 and a high content of carbon, potassium, magnesium, and calcium (plant macronutrients), but also sodium (a mineral which affects negatively on the growth of most crop plants). A co-composting with sewage sludge and woodchips was tried out in a municipal plant some years ago but was not successful because the material was too soft and smeary. Upon drying, the material, which has very fine particles, forms clumps which are hard to break. The material has shown promising characteristics as a soil amendment (Løes et al., 2022), with a long-lasting residual effect on agricultural crops but no immediate fertilizer effect. However, applying the paste material evenly in the field is not straightforward. Hence, it was of interest to test whether composting of this material was possible because this could produce aggregates which are easier to spread in the field.

We have worked on three different scales: Dewar flasks with a volume of 2 liters; in-vessel composting with a volume of 200 liters; and outdoor composting with a windrow. The materials and methods applied, and the outputs and experiences received on each scale, will further be presented in this report. We have followed the IMRAD structure for each level. To avoid the method details becoming too overwhelming, it may be useful to go from methods to results for each level while reading.

Image 1 Compost windrow from algae fiber, acidified fish bone, wood chips, bedding material from dairy calves. Tingvoll Farm, July 20th, 2022. Photo: Joshua Cabell.

2 Materials and methods

2.1 Compost feedstocks

2.1.1 Rockweed (*Ascophyllum nodosum*)

The basis for the composts presented in this report is the brown macroalgae *Ascophyllum nodosum*, commonly known as rockweed (*grisetang* in Norwegian). It grows in coastal areas in the midlittoral zone on both sides of the North Atlantic, from Portugal in the east up to Greenland and across to north-eastern United States. Rockweed is used in many products, including as a raw material for alginate, biopolymers, fertilizers and biostimulants, and as a feed additive for livestock. Many of these processes generate a residue, referred to as algae fiber or filter cake, that has limited use. The Norwegian/Italian company Algea AS harvests wild rockweed from the Norwegian coastline and processes it into a feed additive and various fertilizer and biostimulant products at their facility in Kristiansund, Norway. The feed additive is simply dried and ground rockweed, which is also the raw material for the fertilizer products. The fertilizer products are made using an extraction process utilizing different acids and bases depending on the specific product they are making. The final product is a liquid fertilizer, and the residue is the fiber. In Norway, this fiber is currently being transported 180 kilometers to a municipal waste-to-heat facility where it is incinerated.

Image 2 Left side: close-up photo of algae fiber. "Low-N" and "High-N" look exactly the same. Right side: close-up photo of dried and ground rockweed (commercial product used as feed additive). Photo: Anne-Kristin Løes.

In this study, two types of algae fiber – a “high-N” and a “low-N” – were used as the basis for most of the composts either alone or in combination with other feedstocks. The “high-N” fiber is the result of a process using nitric acid (HNO_3), which gives it a total nitrogen (tot-N) concentration of approximately 1.5% (per dry weight) and a C:N ratio of 22:1. One variant of this type is processed with KOH and another with NaOH. The former is the more common type and the one used for most of the trials. The “low-N” fiber has a tot-N concentration of under 0.5% and a C:N ratio of 74:1. This one is also processed with KOH. Both fibers have a consistency like paste and a dry matter (DM) content of approximately 25-30%. The dried and ground rockweed has the consistency of wheat bran, has a tot-N concentration of 1.4%, and a C:N ratio of 30. This material was not used in any composting trials but has been included as a reference. Table 10 lists results from chemical and physical analyses of several batches of the feedstocks, performed by Nemko Norlab (Norway), Modern Analytics (Greece), and done in-house at Tingvoll Farm.

2.1.2 Tangle kelp (*Laminaria hyberborea*)

We conducted a small experiment with some samples of *Laminaria hyperborea*, a species of brown alga commonly known as tangle or cuvie kelp (*stortare* in Norwegian). It is found only on the northeastern side of the Atlantic Ocean and grows in the sublittoral zone. We were given samples by Nutrimar AS, a Norwegian company that produces feed for salmon and chicken and has a division at Frøya that harvests tangle for use in feed, food, and pharmaceutical products.

Image 3 Fronds of tangle (Laminaria hyperborea): left side rinsed in fresh water; right side not rinsed. Photo: Anne-Kristin Løes.

We were given two samples: one of fresh fronds, and one “waste material” composed of a frond fraction containing small amounts of stipe fragments and epiphytes. Both were vacuum packed and stored at 5 °C. The “fresh” material had a DM content of approx. 17% and the “waste” approx. 15%. The tangle was harvested off the coast of the island of Frøya, Norway. Nutrimar is most interested in the stipes since it is easier to dry and because the alginates from that part of the kelp contain higher levels of guluronic acid. We therefore composted the fresh fronds without stipe (Image 3).

Before composting, we discussed whether the high salt content could hamper the composting process. We rinsed some of the material with tap water and measured the conductivity of the rinse water from rinsing 1, 2, 3, and 4 times (Image 4). In each round of rinsing, the amount of tap water was about equal to the amount of tangle (Image 5).

Image 4 From left: tap water, tap water sieved off after being mixed with tangle fronds round 1, round 2, round 3, round 4. Photo: Anne-Kristin Løes.

Image 5 Rinsing of tangle fronds in tap water, round 1. Photo: Anne-Kristin Løes.

2.1.3 Fish residues

As the main source of nitrogen in the composts we used the residues of captured white fish (cod, haddock, saithe, ling). Several fish processing facilities are located along the north-western coast of Norway and generate residues consisting of bones, spines, heads, tissue attached to the bones, and sometimes skin and viscera – all entrails that remain after processing and fileting. Some also have by-catch or fish that do not meet size or quality standards that must also be disposed of. Such materials have often been applied as feed for fur animals (mink, fox), but this industry was recently prohibited in Norway and hence there is some interest in other utilization.

We used two types of fish residues from these processing facilities in our composting trials. The first was sediment remaining after hydrolyzation of ground-up fish which was acidified (pH <4) with formic acid (Image 6). Upon hydrolysis, the top layers of oil and soluble proteins are pumped off and applied as feed in aquaculture. The remaining sediments must be removed. Such sediment was delivered to NORSØK in IBC tanks in 2018, with a DM content of about 50%, and air-dried before application in field trials (Løes et al. 2022). As a substrate in the windrow compost presented here, the remains from two IBC tanks were applied.

Image 6 Left side: sediments of hydrolyzed, ground, and acidified white fish. Right side: air-dried sediments ready for application in field experiments, or compost. Photo: Anne-Kristin Løes.

Image 7 Cod backbones with flesh after removal of filets for production of clip fish. Photo: Anne-Kristin Løes.

The second material was a dried fish meal made from residues after producing “clip fish” (Image 7) Clip fish is a traditional product made by salting and drying of white fish. The bones were ground and dried in a large rotating dryer (Image 8). The dried flesh turns into a powder that is sieved for use as a protein source. What remains is a meal that contains a mix of bones and protein-rich aggregates of varying sizes. Some varieties of this meal were made from primarily spines and bones, but we used a type that is made from “kleppafisk”, which is composed of whole cod that may be too small (<2.5 kg) to be fileted into clip fish and sorted out, ground up, and dried.

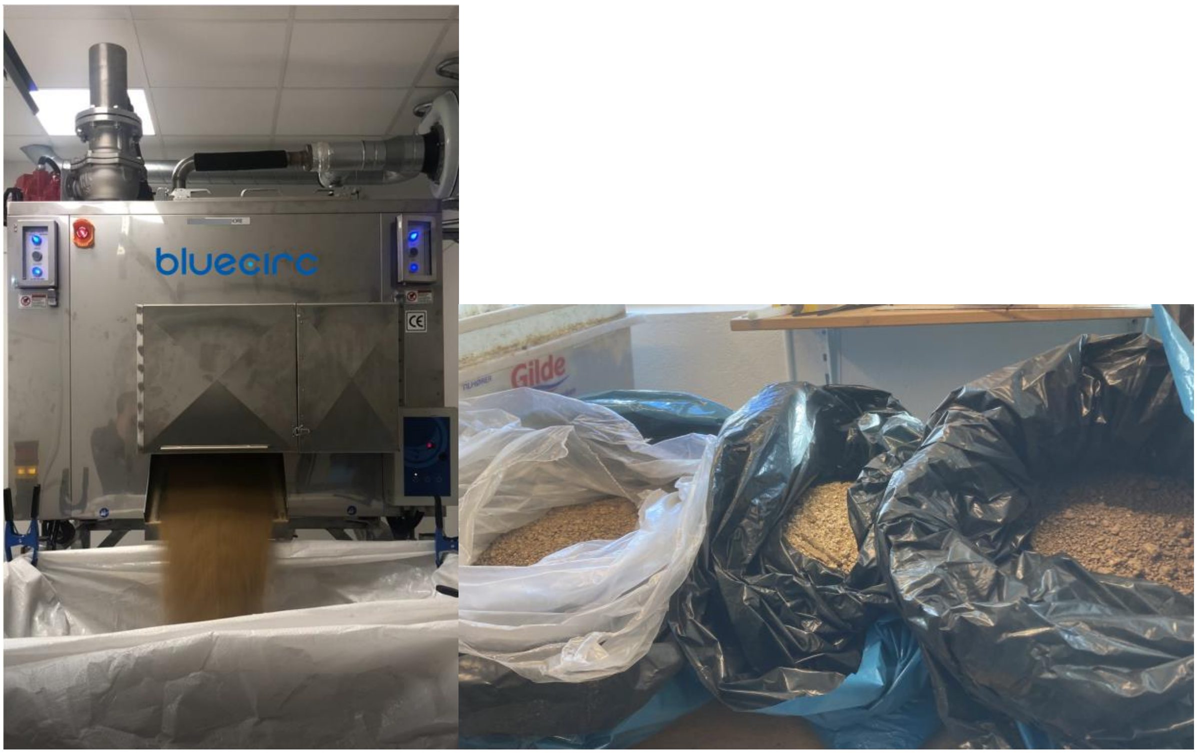

Image 8 Left side: drying, grinding, and sieving of fish spines (or whole fish in the case of "kleppafisk") in a pilot project at Averøy, Norway in 2022 by BlueCirc AS. Right side: remains after sieving off the finest fractions for food and feed purpose. Photo: Bluecirc (l), Anne-Kristin Løes (r).

2.1.4 Non-marine materials

In some of the initial Dewar flask experiments, we used wood chips and barley straw as bulking agents and sources of carbon. We also used horse manure as an inoculum, to add further structure, and as a control, since it is a widely used feedstock for composting. For the windrow composting, we used farmyard bedding comprised of manure and straw collected from the on-site dairy farm and wood chips as sources of carbon and bulking agents. No analyses were made for these materials, but we used previous experience and data from the literature when making the compost recipes. For the tumbler and some of the Dewar flask trials, we used lightweight expanded clay aggregates (brand Leca®) as a bulking agent. The aggregates were sorted to be between 4-10 mm in diameter, rinsed with tap water to remove dust, and dried. The manufacturer delivered the aggregates to us directly from their plant located outside of Oslo. The wood chips have a bulk density (BD) of approximately 0.35 g/cm^3 and the Leca® have a BD of approximately 0.30 g/cm^3.

2.2 Composting equipment

2.2.1 Dewar flasks

Named after its inventor James Dewar, a Dewar flask is an extremely well-insulated vacuum flask originally designed to hold liquid nitrogen (Image 9). The common thermos used to keep drinks warm is a type of Dewar flask. The type used in this experiment is a model 16C produced by KGW-Isotherm GmbH. It has a total volume of 2000 ml, is open at the top, and is lined with Borosilicate glass. These flasks were first used in the context of composting when the Dewar Self-heating Test was developed in Germany in the early 1980s as a method for evaluating compost maturity (Brinton et al., 1995). This method has since been adopted as a standard in other countries. Studies have confirmed that the method can also be used to estimate the potential degradability ("compostability") of fresh materials, as has been done here (Miloştean & Flori, 2021).

Image 9 Dewar flasks filled with feedstock. In front of and to the right of the flasks are two "Thermofox" and "Multisensor", and one "Remotefox" (bottom of photo). In later Dewar trials, the flasks were covered with a breathable cover to reduce heat and water vapor loss. Photo: Joshua Cabell.

2.2.2 Compost tumbler

For producing compost at a mesoscale, we used a compost tumbler produced by Jorakompost®, model 270 (Image 10). This tumbler has a total volume of 270 liters divided into two compartments and is insulated. However, the producer recommends not filling more than half the volume. It rotates on a horizontal axis and is turned by hand. Two vents on either end provide aeration.

Image 10 Jordakompost 270 compost tumbler with one of the compartments open and a temperature sensor visible. The compartments were filled to just above the central axis halfway to the upper vent. Photo: Joshua Cabell

2.2.3 Manure spreader and compost turner

We built a windrow for composting on a larger scale. The raw materials were first mixed in a Gafner® manure spreader (Image 11). This equipment has a belt that pushes the material into rotating knives that cut, mix, and cast it out from the side. An attached screen forces the cast material to fall directly to the ground next to the wagon as it is slowly drawn by the tractor. The windrow was then mixed and aerated with a compost turner produced by Bergrønningen Storfekompost, which is hitched to the tractor and powered by the PTO connection (Image 12). The windrow turner looks like a bridge that spans the windrow with blades attached to a rotating axel cutting across the span. These blades mix the compost as the turner slowly moves forward along the windrow.

Image 11 Left: A view of the algae fiber(the other feedstocks er underneath) and the rotating knives of the Gafner; right: side view of the Gafner as it is depositing the mixed feedstocks. Photo: Joshua Cabell.

Image 12 Photo of the compost turner at Tingvoll Farm, taken on 26.08.2022. Visible on the right is a layer of acidified fish bone, on the left it is blended in. Photo: Anne-Kristin Løes.

2.2.4 Measuring and logging temperature

For measuring and logging temperature in the Dewar flasks and in the tumbler, we used equipment produced by Scanntronik Mugrauer GmbH (Images 9 & 13). The sensors for measuring temperature are a type of NTC thermistor. These were connected either directly to a "Thermofox Universal" data logger, or indirectly via a "Thermofox Multisensor", which is a docking station for up to eight sensors. With the "Multisensor", a total of ten external sensors can be connected per "Thermofox Universal". The "Universal" also has an internal thermistor that measures and logs room temperature. The

“Universal” was connected to a “Remotefox”, which is a wireless, battery-powered GPRS modem transmitter that sends the data over the mobile phone network to an email address. The temperature data were registered every hour and transmitted every 24 hours.

Image 13 Top left: Thermofox Universal; top middle: Thermofox Multisensor; top right: Remotefox; bottom: temperature probe from Sandberger. Photo: Scanntronik (top), Joshua Cabell (bottom).

For measuring the temperature in the windrow, we used a probe produced by Sandburger (Image 13). It has a one-meter-long temperature probe, which we inserted at three different depths (20, 40, and 60 cm from the top) at five points (the two ends, 1 meter in from each end, and in the middle) along the windrow to give us a three-dimensional temperature profile.

3 Methods

3.1 Analysis of feedstocks and compost

The chemical characteristics of fish meal, acidified fish bone, the two algae fibers, the tangle kelp, and compost from the windrow and the tumbler were assessed at SINTEF Norlab Department in Namsos, Norway. The ground rockweed, as well as some individual characteristics of the other feedstocks, were analyzed at Modern Analytics in Thessaloniki, Greece. Modern Analytics is a consortium partner in MARIGREEN. All samples were analyzed for dry matter content (DM, %), loss on ignition (LOI) to assess the mineral content, pH, concentration of total carbon (C) and total nitrogen (N), total organic carbon (TOC), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg) and sodium (Na), and up to 15 additional mineral elements and potentially toxic elements. Modern Analytics did not include the potentially toxic elements in their analysis, nor TOC, chlorine (Cl), molybdenum (Mo), or nickel (Ni).

pH and electrical conductivity (EC) were measured after application of deionized water (v : v 1 : 2.5).

For total C, thermal decomposition at 1200-1500 °C to convert all carbon into CO_2 was applied in a total organic carbon analyzer, including a step to measure CO_2 by a detector, following NS-EN 15936: 2012.

For total N, Kjeldahl-N was applied, where all nitrogen is converted to ammonium sulphate by application of concentrated sulfuric acid, converting ammonium to ammonia gas by application of sodium hydroxide and measuring the amount of ammonia by distillation into hydrochloric acid and measuring the amount of acid not reacting with ammonia.

For determination of chlorine, the sample was extracted with deionized water for one hour, and concentrations measured by ionic chromatography.

Multi-element determination of selected elements by ICP-MS (internal method based on NS-EN ISO 17294-2: 2016) consists of a chemical digestion of the sample by a nitric acid/hydrogen peroxide solution at 120 °C for 30 minutes to bring ions into aquatic solution, followed by a quantitative assessment of concentrations of elements by the measuring instrument, Agilent ICP-MS 7900.

Bulk density was determined at Tingvoll farm by loosely filling a 1-liter cylinder from a height of 45 cm three times and calculating the mean of the weights.

Methods used internally at Tingvoll Farm described in Krogstad (1992).

3.2 Compost recipe calculator

The "recipes" for most composts were made using a calculator developed by Agrilab Technologies, Inc, an American company specializing in designing and building composting facilities with heat recovery (https://agrilabtech.com/). It is an Excel-based calculator that uses moisture content (MC), percent total carbon (C), percent total nitrogen (N), weight, bulk density (BD), and C:N ratio to calculate compost recipes. It also calculates the volume of compost produced per week and year based on the amounts of feedstock one has available. We have modified the original calculator to calculate recipes on smaller scales, including the Dewar flasks.

Where possible, we aimed for a C:N ratio of between 25-40:1, an MC between 50-60%, and a BD between 0.4-0.6 g/cm^3 (or 400-600 kg/m^3) in the combined feedstocks at the start of the trials.

3.3 Dewar Self-heating test

3.3.1 Background of method

The "self-heating test" using Dewar flasks is an established method used to determine compost stability or maturity (BS EN 16087-2:2011). It was first developed in Germany in the early 1980s and further modified by Woods End Laboratories in Maine, USA (Brinton et al., 1995). The method consists of filling 2000 ml flasks with an opening that is 100 mm in diameter with compost, placing them in a room at 20 °C, and monitoring the temperature within the flask. The maturity of the compost is then classified on a scale of I-V either based on how much warmer the temperature in the flask is relative to room temperature or, alternatively, based on the absolute temperature in the flask. This scale is known as the "Rottegrad" classification system, with "I" being "immature" and "V" being "very mature". Each category comes with a list of recommended uses, from feedstock for compost (immature) to potting soil (very mature). Woods End Laboratories recommended reducing the number of categories from five to three in an update from 2009, but the principle is the same.

Table 1 Original Rottegrad Index adapted from Brinton et al. (1995)

Temperature rise above ambient in °C (ambient 20 °C)	Class of stability	Descriptor of class or group
0-10	V	Very stable, well-aged compost
10-20	IV	Moderately stable, curing compost
20-30	III	The material still decomposing, active compost
30-40	II	Immature, young, or very active compost
40-50	I	Fresh, raw compost, recently mixed ingredients

Table 2 Proposed updated Maturity Index from Woods End Laboratories

°C over ambient (approx. 20 °C)	Actual temp in Dewar flask (°C)	Class of stability	Interpretation
0-5	20-25	A	Mature, curing compost
5-25	25-45	B	Mesophilic, active
25-50	45-70	C	Thermophilic, very active

The same self-heating method can be used to test the “compostability” of fresh feedstocks, though it is not as well established nor as commonly used as the maturity/stability test. One of the few references in the literature is from Miloştean and Flori (2021), who conducted such a test with four mixtures of garden and kitchen waste. To eliminate uncertainty in the results, it is crucial to start with the parameters C:N, MC, and BD as close to optimal as possible and as similar as possible between mixtures being tested. Alternatively, one can test the same feedstocks with a range of start parameters to find what is optimal, for example slightly higher or lower C:N ratios, different amounts of bulking material, or a range of moisture contents. According to Miloştean and Flori (2021), a mixture is deemed “compostable” if the temperature rises above 40 °C in the Dewar flask, though this can only be considered as a rough guide since composting at larger scales has different dynamics than in Dewar flasks.

Composting has three general phases defined by temperature and time. The initial phase immediately after mixing lasts only a day or two and has temperatures within the mesophilic range (up to 45 °C). The second phase is where most of the active composting takes place and can last weeks to months with temperatures in the thermophilic range of 45° to 70 °C. When the easily degradable nitrogen and carbon are consumed by the microorganisms or lost to the environment, the compost enters the maturation phase and temperatures drop back to the mesophilic range and eventually reach ambient temperatures. Proper maturation can take months and is an important phase for ensuring compost quality but is often cut short due to practical or economic reasons.

The self-heating test is a practical method for screening raw materials and mixtures before scaling up. For example, we tested the use of Leca® as an alternative bulking agent in Dewar flasks before using it in the tumbler. We were also able to test different ratios of feedstock-to-Leca® to find out which one performed best. Since this was our first experiment with Dewar flasks, we began by filling them with feedstocks commonly used for making compost: horse manure, straw, and wood chips. This was then followed by more experimental feedstocks that to the best of our knowledge have previously not been tested in Dewar flasks such as tangle kelp, algae fiber, fish residues, and Leca®.

3.3.2 Experimental setup

3.3.2.1 Preliminary trials

To get to know the equipment and establish routines, we conducted some preliminary trials. Due to the sheer number of feedstocks, we made a list of codes to identify them. These are listed in Table 3. The first mixture we experimented with was a 3:1 blend of fresh horse manure and chopped barley straw (Table 4). This combination is well documented as being optimal for making compost. It has almost the perfect C:N ratio and bulk density and is full of microorganisms that rapidly initiate thermophilic decomposition. Other treatments included the same mixture (horse manure and straw) but with wood chips added for more aeration; tangle kelp and straw; rinsed (with tap water) tangle kelp and straw; and rinsed tangle kelp, straw, and horse manure. In a second round of the preliminary trial, we tested algae fiber (both “low-N” and “high-N”) mixed with fish meal and either straw or wood chips as the bulking agent, and with and without horse manure (Table 4). The idea of adding the horse manure was that it would affect the microflora of the compost mixture and hence support the thermophilic processes and heat development.

Table 3 Codes assigned to the feedstocks.

Feedstock	Abbreviation
Horse manure	HM
Barley straw	S
Tangle Kelp	K
Wood chips	WC
Leca®	L
Algae fiber “low-N”	AFLN
Algae fiber “high-N”	AFHN
Ground rockweed (seaweed)	GSW
Dried fish meal	FM

Too high salinity can be problematic both for composting and for plants. We wanted to compare composting tangle “as is” with tangle that was rinsed with fresh water and see if rinsing made any difference in the thermodynamics of composting. We rinsed a fraction of the tangle with four rounds of fresh tap water and measured the electrical conductivity (EC) in each portion of the rinse water (Images 4 & 5). Not surprisingly, the EC decreased with each rinse, confirming that we removed a portion of the salt from the tangle.

The horse manure and algae fiber treatments were mixed in bulk and then divided into two replicates. The Dewar flasks were filled with approximately 2 liters of material, weighed, and placed in a room with no windows, where the temperature was set at ca. 20 °C. The horse manure treatments were mixed on 22.04.22 and the rest were mixed on 03.05.2022. All flasks were weighed and emptied on 19.05.2022. The contents were thoroughly blended before the flasks were refilled for a second round of possible heat generation. On 27.06.2022, the flasks filled with the horse manure and tangle treatments were emptied, and the flasks with algae fiber, where the initiation of heat occurred later than for horse manure and tangle, were emptied and refilled for a second time. These were then finally emptied on 05.07.2022.

Table 4 Combinations of feedstocks for initial Dewar experiments

Mixes	Ratios (v:v)	Water (ml)
HM+S	3:1	0
HM+S+WC	6:2:1	0
K+S	1:1	0
K (rinsed)+S	1:1	0
K (rinsed)+S+HM	3:3:1	0
AFLN+FM+S	3:1:5	150
AFLN+FM+S+HM	6:2:10:1	150
AFLN+FM+WC	3:1:5	150
AFLN+FM+WC+HM	6:2:10:1	150
AFHN+FM+S	18:1:31	150
AFHN+FM+S+HM	18:1:31:3	150
AFHN+FM+WC	18:1:31	150
AFHN+FM+WC+HM	18:1:31:3	150

3.3.2.2 The Leca® experiments

One of the three most important parameters in making compost is to have a good structure that provides an adequate amount of porosity and free air space that supplies the microorganisms with oxygen. This is also referred to as “bulk density”. Too little porosity (too dense) leads to anaerobic conditions, and too much porosity can lead to excessive heat and water loss. Both conditions lead to cold and inactive compost. We were interested in finding a bulking agent that contributes nothing other than structure to the compost. Wood chips or other woody materials are often used, but they also contribute carbon. We decided to experiment with Leca® since it is largely inert. The material is used for building and road construction, but also in horticulture and hydroponics. It adds bulk and is very porous, providing a large surface area for microorganisms to colonize and for water storage. To find the optimal ratio of Leca®-to-feedstock, we conducted two basic experiments (Table 5). The first was with varying amounts of Leca® mixed with algae fiber, fish meal, and horse manure. In the second experiment, we mixed only algae fiber “high-N” with Leca®. However, for this experiment, we had two different versions of this algae fiber. One was treated with potassium hydroxide (KOH) and the other was treated with sodium hydroxide (NaOH). The former is more common and the one we used in all the other experiments.

Table 5 Feedstocks for Leca® experiments

Mixes	Ratios (v:v)
HM+AFHN+FM+L	3:3:1:3
HM+AFHN+FM	3:3:1
AFHN+FM+L	3:1:2
AFHN(Na)+L	3:1
AFHN(Na)+L	1:3
AFHN(K)+L	3:1
AFHN(K)+L	1:3

The first three blends with algae fiber, horse manure, and fish meal were made on 05.05.2022 and placed in an unheated room. They remained here until 29.05.2022. The blends with exclusively algae fiber and Leca® were mixed on 06.10.2022 and placed in a room heated to 20 °C. These remained here until 06.12.2022.

3.4 Tumbler composting

We made a batch of compost in the Jordakompost 270 to be applied for extraction of possible biostimulants. This compost contained only algae fiber "high-N", Leca®, and a small amount of granulated sugar added after about two weeks (05.01.2023) to raise the C:N ratio. The experiment began on 21.12.2022 with the following recipe:

Table 6 Tumbler compost recipe

Feedstock	Volume (liter)
Algae fiber "high-N"	50
Leca®[1]	15
Granulated sugar[2]	1.5

[1] On 02.01.2023, the ratio of Leca-to-algae fiber was increased to 1:1 in one of the compartments.

[2] On 05.01.2023, 1000 g and 500 g of granulated sugar was added to the compartment with the original mixture and to the compartment with extra Leca, respectively.

Table 7 Tumbler feedstock characteristics at the start (estimated)

Parameter	Value
C:N ratio	23 (35)*
Bulk Density	630 kg m^{-3}
Moisture Content	60%

*Start C:N was 23, and was in theory raised to 35 when sugar was added

The feedstocks were measured by volume using graduated 30-liter buckets and mixed by hand and with a shovel in a plastic container. This mixture was then divided into two even portions, one for each compartment in the tumbler. The compartments were filled to just above the halfway mark. Two temperature sensors were fastened to the center axle, one in each compartment. These were then connected to a "Thermofox Universal" which was in turn connected to a "Remotefox" (Image 11). The temperature in each compartment was logged automatically and sent every 24 hours. We also recorded the temperature manually each time we rotated the tumbler (3x around) on Monday, Wednesday, and Friday.

The tumbler was initially placed in an unheated room where the temperature varied between 2.1 and 4.6 °C. We thought that the insulation in the tumbler would be enough to retain the heat generated by the compost, but it was not. A heater was placed in the room on 02.01.2023 and the temperature was raised to approx. 15 °C. On 19.01.2023, the tumbler was emptied and moved into an adjoining room with in-floor heating, and then filled again. In this room, the temperature varied between 13 and 19 °C.

We decided to increase the amount of Leca to approximately 50% of the substrate volume in one compartment, to see if this could increase the development of heat. This was done on 02.01.2023 by taking out approximately 15 liters of the original mix from the compartment on the right side and then mixing in approximately 16 liters of Leca® with the substrate which was left in the compartment. This increased the ratio of Leca®-to-algae fiber from 1:3 to 1:1. In addition, we added granulated sugar to both compartments on 05.01.2023. This was done to increase the carbon content, which was relatively low to begin with, and to stimulate another round of heat generation. 1000 g was added to the side with the original mixture, and 500 g to the side with extra Leca®.

3.5 Windrow composting

A windrow is simply an elongated pile and is one of the most common methods for composting at larger scales. It is an efficient method for managing large quantities of diverse feedstocks and with the right equipment and regular turning produces a homogenous compost.

Image 14 The Gafner farmyard manure spreader with the windrow it just made. Photo: Joshua Cabell.

The windrow was made on 14.07.2022 (Image 14) with the following recipe:

Table 8 Windrow compost recipe

Feedstock	Approx. volume (m^3)
Algae fiber "high-N"	1.6
Algae fiber "low-N"	1.5
Cattle bedding	0.5
Horse manure	0.3
Acidified fish sediment	0.7*
Wood chips	3
Total	**7.4**

* Acidified fish sediment was added three times – 1/3 at the beginning, 1/3 prior to the first turning on 26.08.2022, and 1/3 prior to the second turning on 16.09.2022.

And with the following start parameters:

Table 9 Windrow feedstock characteristics at the start (estimated)

Parameter	Value
C:N ratio	27
Bulk Density	600 kg m^{-3}
Moisture Content	61%

The materials were first loaded in layers into the Gafner farmyard manure spreader wagon. The windrow was then made by driving the tractor slowly forward while the material was deposited on the ground alongside the wagon. The dimensions of the windrow were approximately 4m long by 1m wide by 1,5m high. We covered the windrow with a breathable composting fabric to protect it from precipitation and sunlight.

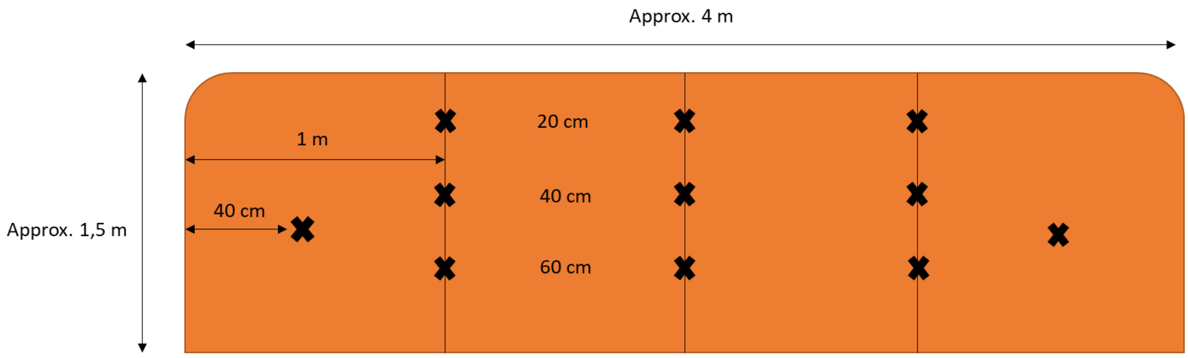

Figure 1 Illustration of compost windrow. "X" marks where the temperature was measured.

We measured and registered the temperature in the windrow each Monday, Wednesday, and Friday (with some exceptions) in the period 19.07.2022-30.09.2022. The temperature was measured at depths 20, 40, and 60 cm below the surface at three points: one meter in from either end, one point in the middle, and at the ends of the windrow at approx. halfway down and 40 cm in (Fig. 1). On 26.08.2022 and again on 19.09.2022, we added another 1/3 of the acidified fish sediment to the top of the windrow and then mixed it in with the windrow turner.

The last temperature measurement was taken on 30.09.2022 and the windrow was left to cure. Approximately 120 liters of compost were removed on 16.02.2023 for further studies such as extraction of possible biostimulants, and a representative sample was taken and sent for analysis.

4 Results and discussion

4.1 Analysis of marine feedstocks

With these analysis results, we were able to make compost recipes based on the C:N ratios, dry matter content (or moisture content), and bulk density. The other characteristics like P, K, S, micronutrients, and concentrations of potentially toxic elements (heavy metals) are more relevant when the compost is applied as a soil amendment. Na-concentration is also an important characteristic to follow as it can be harmful to plants and is a particular challenge with marine residues.

Fish meal, acidified fishbone, algae fiber "high-N", and the tangle kelp can be considered nitrogen sources due to their relatively low C:N ratios (5, 4, 23, and 15, respectively). Ground rockweed, which we did not use in any of the trials presented here (but which is the source of the algae fibers) has approximately the optimal C:N ratio by itself (30:1). The same is the case with horse manure, which we did not analyze for these trials but know from previous experience. The fish meal and acidified fishbone are rich in total-N (7.9% and 4.2% of DM), P (5.6% and 10.3%), and Ca (11.0% and 13.9%), contain some S (0.6% and 0.4%), and little K (0.8% and 0.1%) and Mg (0.3% and 0.1%). Unlike the fish residues, the algae fiber "high-N" has a relatively low concentration of P (0.4% of DM), but higher concentrations of K (9.2%), S (1.2%), and Mg (1.5%). The K likely comes from the fiber being treated with KOH, which also gives it a high pH (9.1). The algae fiber "low-N" is similar to high-N in almost all respects except N-concentration (0.7% of DM) and therefore has a much higher C:N ratio (74:1 vs. 23:1). It also has a slightly lower concentration of K and slightly higher concentration of Ca (Table 10).

Table 10 Analysis results for the marine residues tested in the composting trials. Analyses conducted by Nemko Norlab (Norway) except where marked. Analysis results for acidified fishbone and the two algae fibers were originally published in Zikeli et al. (2022).

Characteristic	Unit	Fish-meal	Acidified fishbone	Ground rockweed[1]	Algae fiber “high N”	Algae fiber “low-N”	Tangle “raw” (dried)
Physical characteristics							
Dry matter	%	90	49	93	26	22	94
LOI	% of DM	66	39	-	54	56	66
pH	H_2O	6.3[2]	4.6	6.1[2]	9.1	8.9	5.6
Bulk Density[2]	g/cm^3	0.81	0.90	0.75	0.81	0.81	-
Macronutrients and carbon							
Tot-C	% of DM	36.0	15.8[1]	37.8	38.5[1]	-	27
TOC	% of DM	0.4	17.2	-	31.7	33.2	-
Kjeldahl-N	% of DM	7.9	4.2	1.3	1.4	0.7	1.8
C:N	Ratio	5	4	30	23	74	15
P	% of DM	5.6	10.3	0.1	0.3	0.4	0.4
K	% of DM	0.8	0.1	1.9	9.2	6.8	9.9
S	% of DM	0.6	0.4	2.6	1.2	1.3	1.7
Ca	% of DM	11.0	13.9	1.9	5.4	8.4	1.2
Mg	% of DM	0.3	0.1	0.9	1.5	1.3	0.7
Micronutrients							
B	mg kg^{-1} DM	-	3	118	72	38	77
Cl	mg kg^{-1} DM	-	14	-	13	<3	-
Cu	mg kg^{-1} DM	1.9	5.7	3.0	11.0	<2	0.9
Fe	mg kg^{-1} DM	61	1276	198	195	430	34
Mn	mg kg^{-1} DM	7.8	18.3	21	51	24	2.4
Mo	mg kg^{-1} DM	<0.2	0.4	-	-	<2.0	0.1
Ni	mg kg^{-1} DM	48	4	-	4.4	18	0.7
Zn	mg kg^{-1} DM	64	126	37	95	38	100
Other							
As	mg kg^{-1} DM	16	3	-	28	19	>30
Cd	mg kg^{-1} DM	0.05	0.13	-	1.00	0.91	0.25
Co	mg kg^{-1} DM	0.05	0.6	-	2.1	<1.0	0.29
Cr	mg kg^{-1} DM	0.8	7.9	-	6	35	0.4
Hg	mg kg^{-1} DM	<0.7	0.23	-	0.04	0.10	<0.70
Na	% of DM	1.8[1]	0.7[1]	3.3	1.7[1]	-	3.4
Pb	mg kg^{-1} DM	<0.09	1.5	-	1.4	3	<0.06

[1] These analyses were conducted by Modern Analytics in Thessaloniki, Greece.

[2] These were determined at Tingvoll Farm.

4.2 Dewar self-heating trials

4.2.1 Horse manure

When the temperature logger was connected on day 4 after filling the flasks, the temperature was between 53 and 62 °C (Figure 2), dropping to room temperature after about 1 week. This confirmed that the Dewar flasks could be used with fresh materials and that horse manure could be used as a positive control if required to assess how warm various feedstocks can get in the flasks.

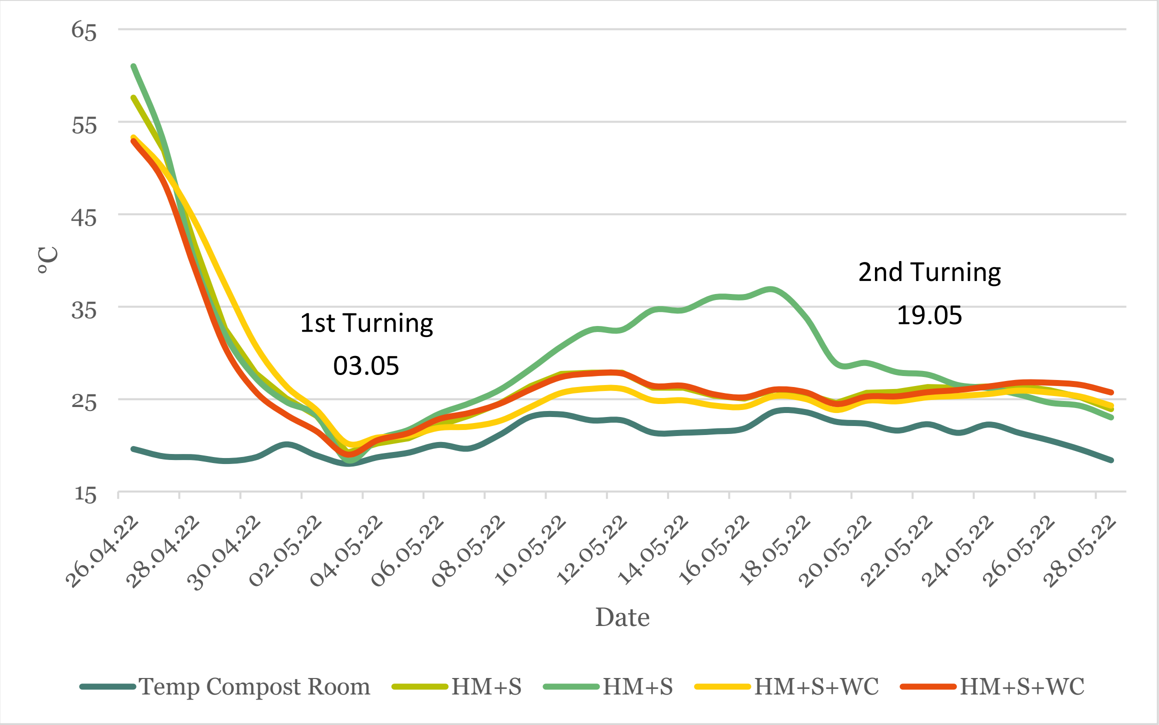

Figure 2 Self-heating trials with horse manure (HM) and straw (S), without (HM+S) and with wood chips (HM+S+WC).

In this trial we had two mixtures of straw and horse manure, and two with wood chips in addition to the straw. The differences were not great as the temperatures followed each other closely. The mixtures with only horse manure and straw were slightly warmer, one of which was significantly warmer after the first turning. Otherwise, there was surprisingly little heat generation after the first turning.

When we emptied the flasks at the conclusion of the trial, we saw that there had been little physical degradation of the feedstocks despite the thermophilic temperatures (Image 15). The straw and wood chips were still intact, and it was evident that a ready-to use-in field compost is not produced in a Dewar flask.

Image 15 Photos taken on 28.06.2022 of horse manure plus straw (top row) and horse manure, straw, and wood chips (bottom row) upon completion of the trial. The straw and wood chips are still largely intact despite having reached thermophilic temperatures. Photo: Joshua Cabell.

4.2.2 Tangle kelp

The purpose of this experiment was to test if rinsing some salt from tangle kelp made any difference in heat generation. The conductivity was reduced in each round of rinse water, from 163 cS m^{-1} down to 49 after the fourth rinsing (Images 4 & 5, Fig. 3). Tap water had a conductivity of just under 2. The rinsing helped to speed up heat generation (Fig. 4) but had little effect on the maximum temperature reached. In fact, the unrinsed maintained a higher temperature over a longer period. This indicates that the microorganisms responsible for the heat development were not negatively affected by a saline environment. The addition of horse manure gave a slightly higher temperature, but the change in temperature over time was very similar to rinsed kelp with only straw (Fig. 4). Per definition, the temperature did not reach thermophilic (> 45 °C) in any of the treatments.

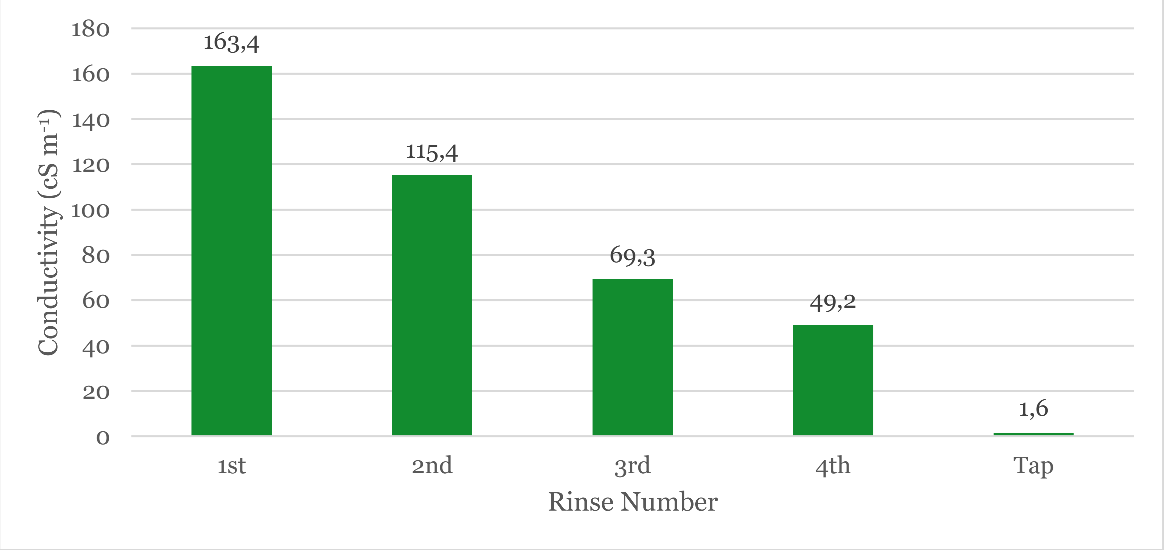

Figure 3 Conductivity in rinse water for consecutive rinses of tangle kelp using tap water.

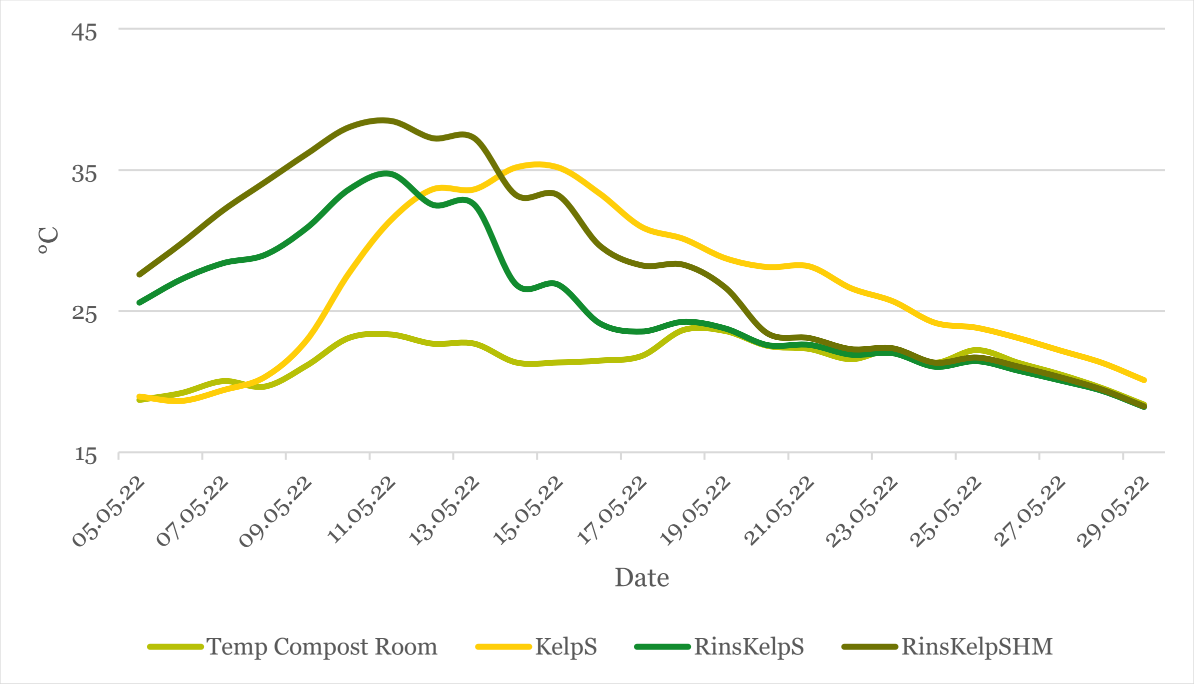

Figure 4 Effect of rinsing tangle kelp on temperature dynamics compared with not rinsing. The unrinsed kelp was mixed with straw (KelpS); the rinsed kelp ("RinsKelp") was composted together with straw (S) and straw plus horse manure (SHM).

4.2.3 Algae fiber

Horse manure is known as one of the best feedstocks for making compost, which was confirmed in the first trial in which the temperature reached up to 62 °C in the Dewar flasks. Algae fiber was new to us as compost feedstock, and we were uncertain if it could be used as a primary feedstock. We also wanted to see if there was a difference between "high-N" and "low-N" algae fibers. When algae fiber was mixed with fishmeal and straw (Table 4), both types of fiber developed significant heat

(Figs. 5 & 6), with maximum temperatures reaching 55 °C before turning and up to 57 °C after turning for low-N type (Fig. 5). Replacing the straw with woodchips did not significantly affect the temperature dynamics. The high-N algae fiber did not reach more than 53 °C and were thermophilic for a shorter time. The temperature reached only a maximum of 35 °C after turning (Fig. 6).

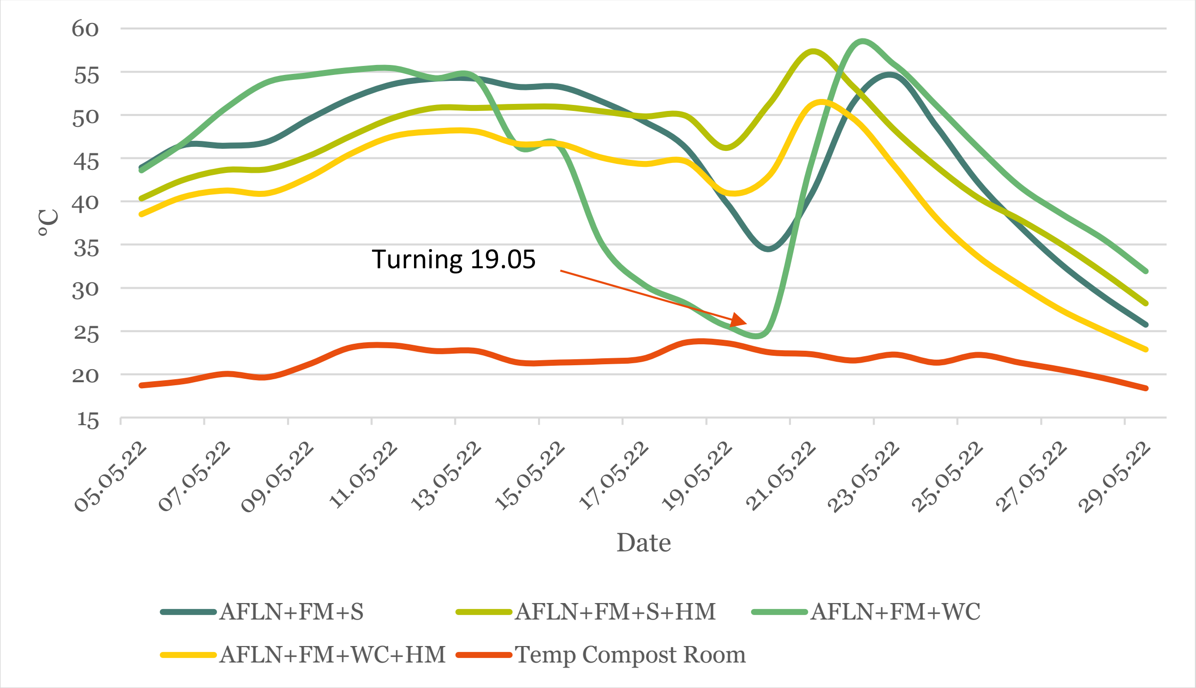

*Figure 5 Temperature in initial Dewar self-heating trials for algae fiber type "**Low-N**" (AFLN) composted together with fishmeal (FM), straw (S), horse manure (HM), and wood chips (WC).*

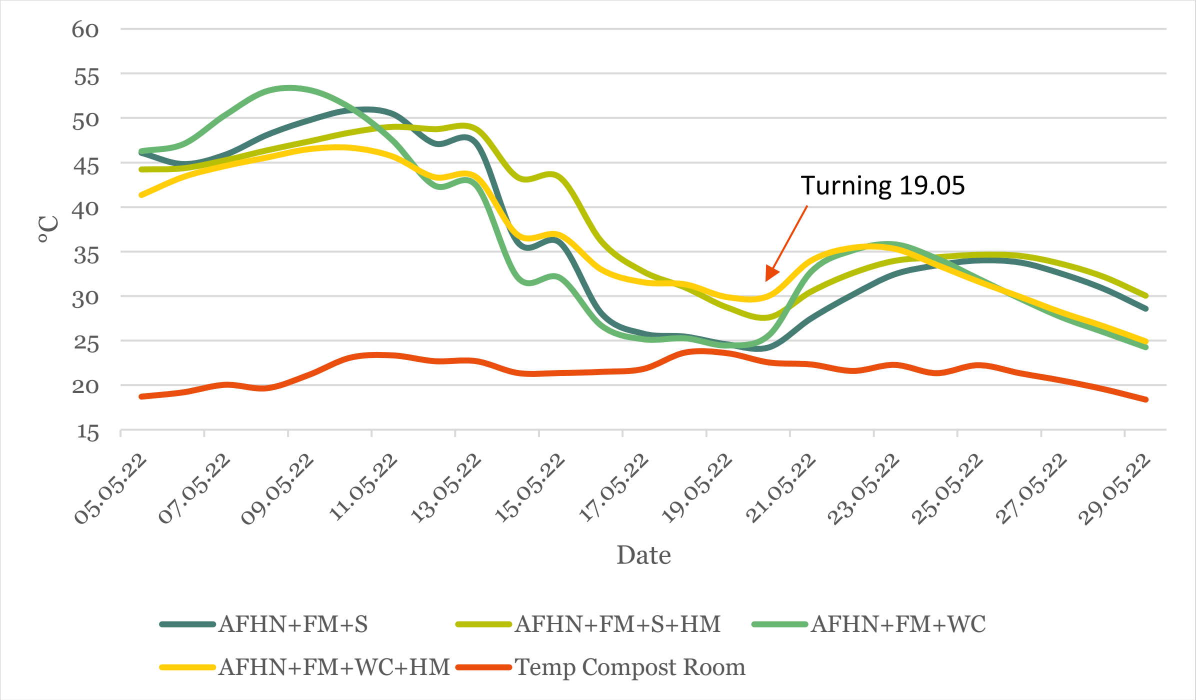

*Figure 6 Temperature in initial Dewar self-heating trials for algae fiber type "**high-N**" (AFHN) composted together with fishmeal (FM), straw (S), horse manure (HM), and wood chips (WC).*

Compared with using horse manure as the primary feedstock, the mixtures with algae fiber as the primary feedstock maintained their heat over a longer period and, especially in the case of the “low-N” treatments, responded very well to being “turned”. The treatment “AFLN+FM+S+HM” had the highest mean temperature of 46 °C in the period 05.05-29.05, and “AFLN+FM+WC” had the highest single temperature of 59 °C. The higher heat development was linked to a larger reduction in volume (Image 16).

Image 16 Photo on the left of algae fiber "Low-N" with a lower volume than flasks with "High-N" on the right, taken on 07.07.2022. The lower volume in the flasks with “Low-N” is likely a result of higher temperatures and more decomposition during the trial. Photo: Joshua Cabell.

Image 17 Photos of the contents from the first algae fiber Dewar trial, taken the day they were finally emptied on 23.09.2023. Top row all with algae fiber low-N, fish meal, and (l-r): straw; straw + horse manure; wood chips; wood chips + horse manure. Bottom row all with algae fiber high-N, fish meal, and (l-r): straw; straw + horse manure; wood chips; wood chips + horse manure. Photo: Joshua Cabell.

As with the first horse manure experiment, the larger, coarser feedstocks like straw and wood chips were largely intact after five months in the Dewar flasks and after having gone through two rounds of thermophilic phases as in the case of low-N algae fiber (Image 17, Figs. 5 & 6). The treatments with low-N and wood chips also had more fungus than the other treatments (photos 3 & 4 in the top row in Image 17).

4.2.4 Leca® experiments

Straw and wood chips are commonly used as bulking agents in compost. However, in MARIGREEN we ultimately wanted to test making composts with exclusively marine-derived feedstocks. Wood chips contain significant amounts of carbon, but a very small proportion of this C is available for thermophilic microorganisms, and this amount is dependent on the quality of the wood and storage conditions. The overall aim of our composting trials is to study the production of humic substances in the compost. We want to see if humic substances could be formed from exclusively marine feedstocks, and it would have been difficult to determine the effect the addition of woodchips or other organic substrates could have in the formation of humic substances. Hence, we decided to test Leca® as an alternative bulking agent that adds structure, aeration, water-holding capacity, and a porous surface for microorganisms to inhabit, but no C or N.

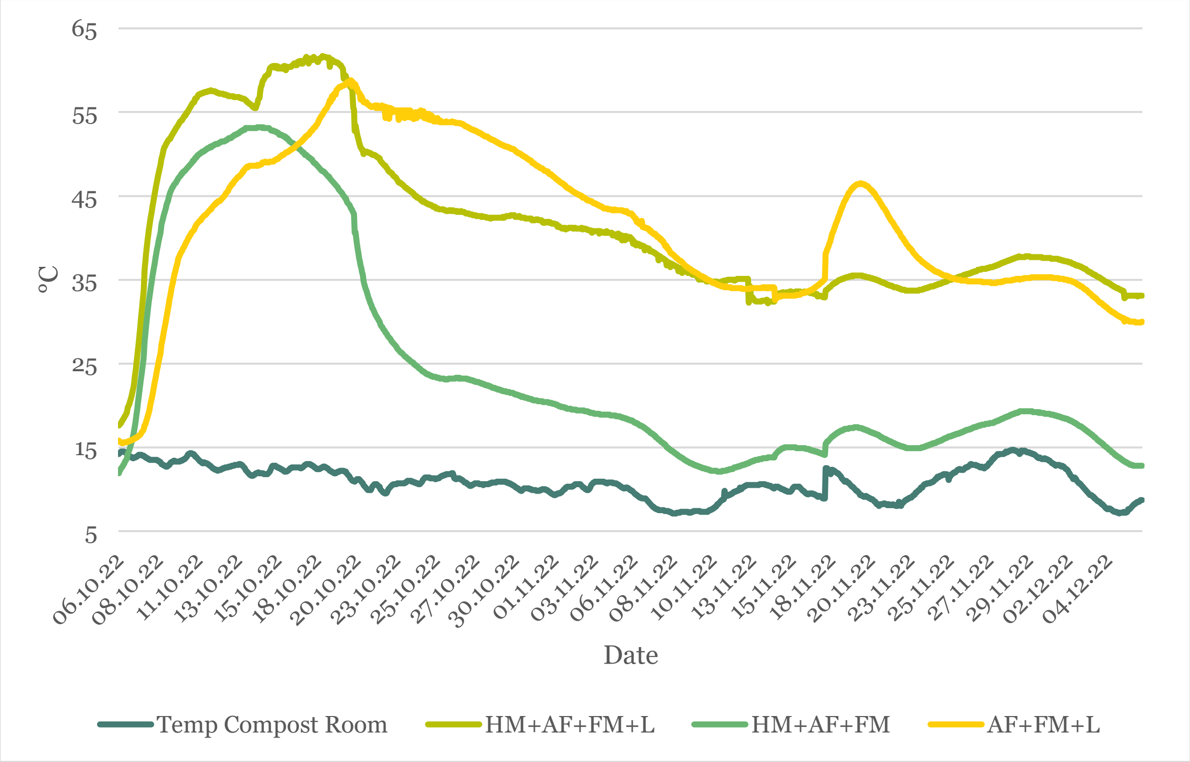

Figure 7 First trial testing Leca® as a bulking agent using three different recipes. All three contain algae fiber "high-N", one with horse manure, fishmeal, and Leca® (HM+AF+FM+L), another with the same feedstocks but without Leca® (HM+AF+FM), and one with Leca® but without horse manure (AF+FM+L).

We applied three different mixes with algae fiber "high-N" as the main substrate (Images 18 & 19). The addition of Leca® increased the heat generation in the flasks. Both mixtures with Leca® reached higher temperatures and maintained them longer than the mixture with no Leca® (Fig. 7).

Image 18 Photo from the first Leca® trial taken on 14.11.2022. Horse manure + algae fiber + fish meal + Leca®; horse manure + algae fiber + fish meal; algae fiber + fish meal + Leca® (l-r). Photo: Joshua Cabell

Image 19 Close-up photos of compost from the second Leca® trial in which only algae fiber and Leca® were used. Photo: Joshua Cabell.

Despite a generally lower temperature in the room during this trial (10-15 °C compared with about 20 in a standard trial), the peak temperatures, also for the treatment with no Leca®, were higher than in the initial trial with high N algae fiber (Figures 5 & 6). The reason why this treatment had higher heat development than the treatment with algae fiber, fish meal, straw, and horse manure may be that the ratio of horse manure to algae fiber was much higher in the Leca®-trial (compare Tables 4 & 5). The horse manure could also be the reason for high heat development in the HM+AF+FM+L treatment, but since a quite similar heat profile was also achieved with no horse manure in the AF+FM+L treatment, the Leca® demonstrated a positive effect (Fig. 7).

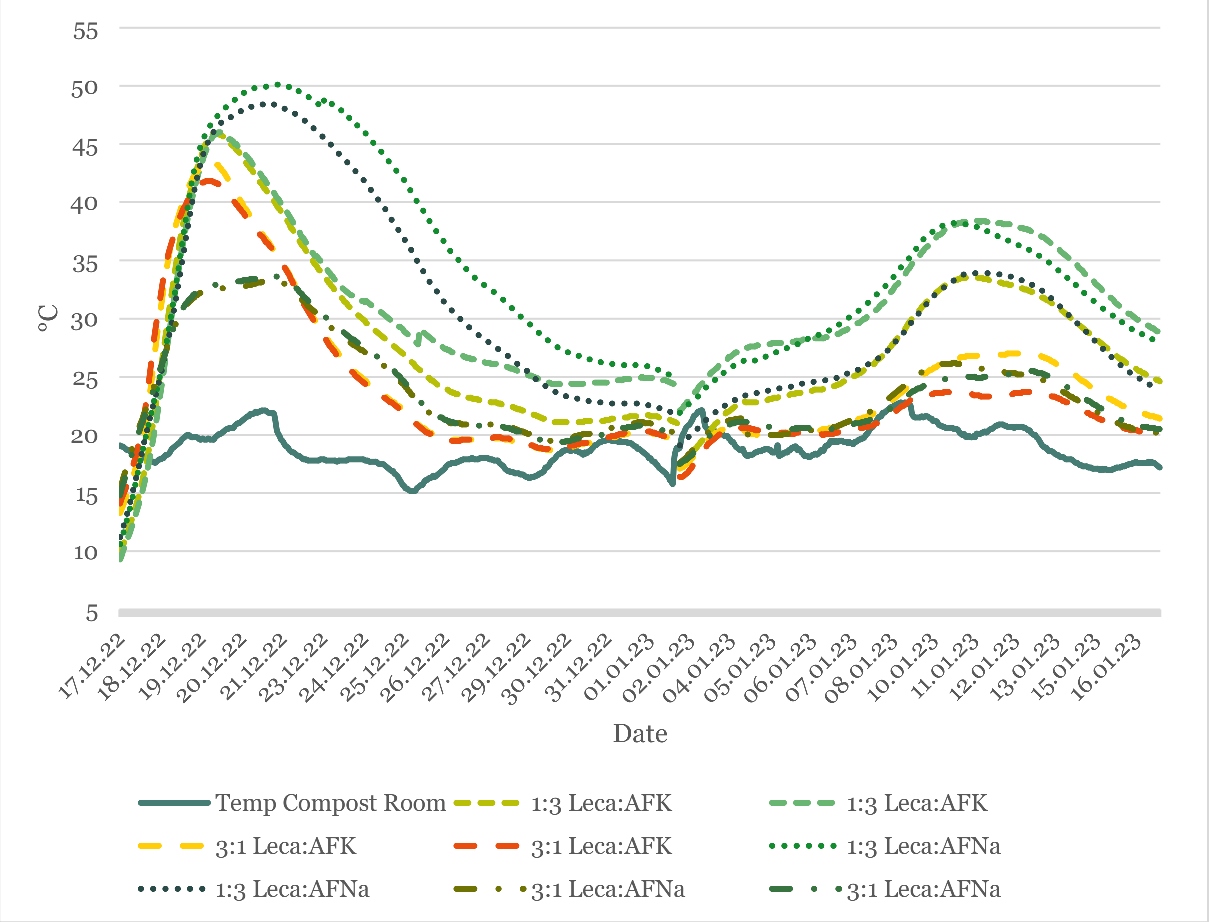

Figure 8 Trial conducted with two ratios of algae fiber-to-Leca® and algae fiber "high-N" with K (AFK) and with Na (AFNa). 1:3 treatments had one part Leca® and three parts algae fiber, whereas 3:1 had three parts Leca® and one part algae fiber. No other feedstocks were added.

A compost that is too dense can become anaerobic whereas a compost that is too porous loses heat and water vapor. Both can lead to cold or inactive compost. In the second Leca® experiment, different ratios of Leca® and algae fiber were tested, with two types of "High-N" fiber. The temperature curves in paired flasks followed each other quite well (Fig 8), and the temperatures were generally somewhat higher with the Na-type algae fiber. The results show that a ratio of 1:3 Leca®:AF performed best. This experiment also demonstrated that it was possible to achieve thermophilic conditions (> 45 °C) using exclusively algae fiber and a bulking agent, with no addition of fish meal or horse manure. The treatment "1:3 Leca:AFNa" had the highest mean temperature of 34 °C during the period 17.12.2022-16.01.2023 and the highest single temperature of 50 °C.

4.3 Tumbler

The temperature in the tumbler never reached a thermophilic phase (> 45 °C; Fig 9). This is likely because the ambient temperature in the room was too low, and the tumbler did not have enough insulation. It could also be because the temperature sensors were near the top of the mass and did not register the temperature at the core. When the ambient temperature was increased to > 10 °C, the temperature in the tumbler also increased to at least within the mesophilic range (> 25 °C), but the temperature curves inside the tumbler consistently followed the room temperature, indicating that the heat production could never account for heat loss. Opposite to what we expected, the addition of Leca® to the right chamber decreased the temperature slightly. This may have been due to decreased bulk density with a more porous structure which promoted heat loss. The addition of sugar on 09.01.2023 gave a very short-lived boost before the temperature dropped again and became parallel to the room temperature. The emptying and re-filling of the tumbler after moving it to a smaller room on 19.01.2022 stimulated a brief rise in temperature faster than the temperature in the room increased, but even with a temperature close to 20 °C in the room, the tumbler lost too much heat to allow for a proper self-heating of the material comparable to what was achieved in the Dewar flasks, or all the easily degradable C and N was already consumed.

Figure 9 Temperatures recorded in compost tumbler from 21.12.2022-01.02.2023. The left chamber contained the original mix of Algae fiber and Leca®, the right chamber was given more Leca® on 02.01.2023. A heater was placed in the room on 02.01.2023, granulated sugar was added to both chambers on 09.01.2023, and the tumbler was moved to a smaller room on 19.01.2023.

4.4 Windrow

The temperature in the windrow increased almost immediately after being built on July 12, 2022 (Image 20, Fig. 10). The difference in temperature between the two ends (left, L, and right, R) was significant, but not systematically different. The differences between measuring depths were also significant. The temperature was mostly highest at 40 cm depth until the second turning. The highest single temperature of 63 °C and the highest mean value of 39 °C during the period 19.07-30.09 was at this depth. Turning with the addition of fish sediment led to increases in temperature.

Image 20 Photo of the windrow and steam coming off. The cover, visible on the far end of the windrow, has been drawn back for registering the temperature. Photo was taken on 18.07.2022. Photo: Joshua Cabell.

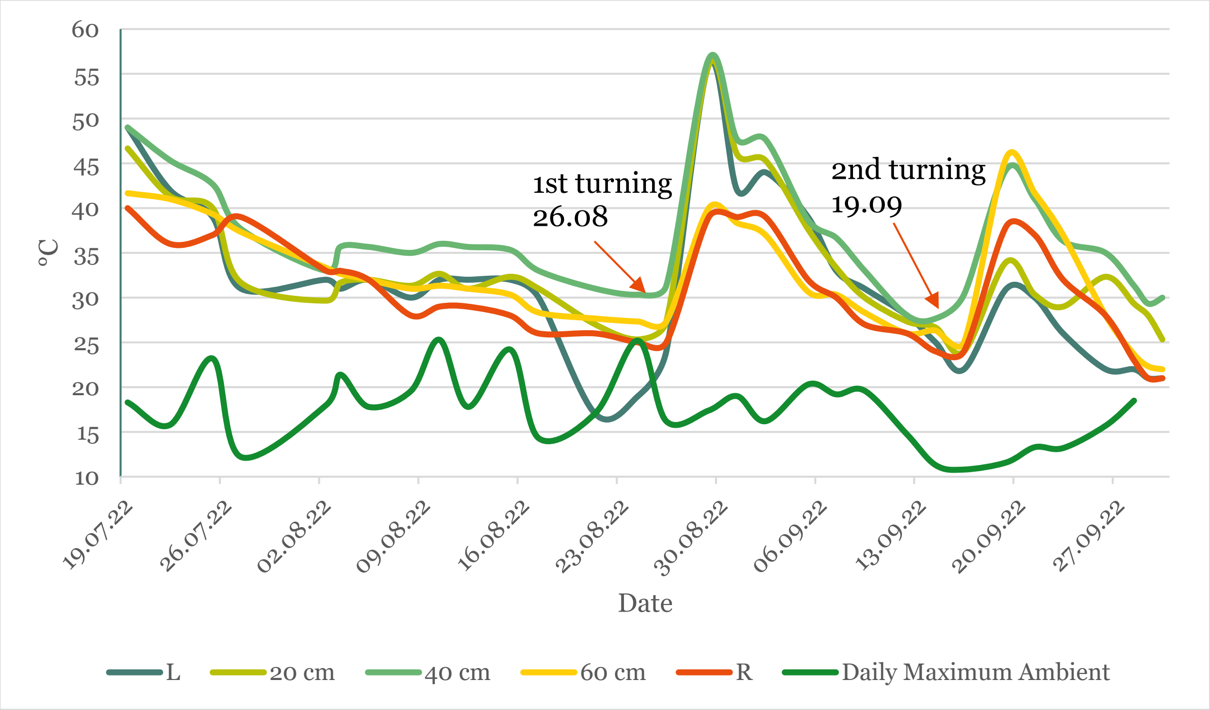

Figure 10 The average temperature for each depth (20, 40, and 60 cm from the top) and the two ends (L and R) of the compost windrow. Temperatures were recorded regularly, approximately 3x per week, from 19.072022-30.09.2022.

4.5 Chemical characteristics of tumbler and windrow composts

Table 11 Analysis results for windrow and tumbler composts.

Characteristic	Unit	Windrow	Tumbler
Physical characteristics			
DM	%	36	39
LOI	% of DM	40	36
pH	H_2O	9.23	9.75
EC	(mS m^{-1})	1000	1100
Macronutrients and carbon			
Tot-C	% of DM	18.8	20.0
Kjeldahl-N	% of DM	1.3	0.5
C:N	Ratio	14	38
P	% of DM	5.0	0.2
K	% of DM	4.5	6.2
S	% of DM	0.8	0.7
Ca	% of DM	18.0	6.5
Mg	% of DM	1.5	2.8
Micronutrients			
Cu	mg kg^{-1} DM	6	10
Fe	mg kg^{-1} DM	1900	3500
Mn	mg kg^{-1} DM	93	87
Mo	mg kg^{-1} DM	1.1	0.9
Ni	mg kg^{-1} DM	5	34
Zn	mg kg^{-1} DM	130	67
Other			
As	mg kg^{-1} DM	16	17
Ag	mg kg^{-1} DM	0.4	0.3
Al	mg kg^{-1} DM	680	1800
Cd	mg kg^{-1} DM	1.3	1.3
Co	mg kg^{-1} DM	1.1	3.2
Cr	mg kg^{-1} DM	4	35
Hg	mg kg^{-1} DM	<0.70	<0.70
Na	% of DM	1.7	1.2
Pb	mg kg^{-1} DM	0.75	0.85

Analysis results presented in Table 11 show that compost from the windrow is relatively rich in N, P, K, and especially Ca. This is obviously due to the addition of other materials than algae fiber, such as manure and fishbones, because the nutrient concentrations of the tumbler compost are very low, except for K. The windrow compost also has a relatively low C:N of 14:1, down from an estimated ratio of 27:1 at the start. The final C:N ratio of the tumbler compost (38:1), on the other hand, is still relatively high. It is higher than that of the algae fiber alone (22:1). Rather than adding sugar to raise the C:N ratio we probably should have added a nitrogen source as the carbon in algae fiber is likely stable and not easily degraded. The concentration of total-N decreased from 1.4% (of DM) at the start to 0.5% after composting. Total-C also decreased, from 38.5% (of DM) to 20%, but this reduction was relatively less than for N. The opposite was the case for the windrow compost, which had a greater reduction of C than N and is more in line with what one normally expects during composting. LOI was reduced for the tumbler compost, from a start of 54% of DM to 36%, due to the volatilization of easily degradable carbon and other organic elements.

The pH for both composts was relatively high (over 9) and increased slightly for the tumbler compost relative to the non-composted algae fiber.

5 Conclusions

A lot of useful experience was gained from these initial trials, which has been applied to the planning of more in-depth Dewar flask experiments that were conducted later in the MARIGREEN project. In these initial trials, we demonstrated that Dewar flasks are a useful tool for testing the suitability of various feedstocks and combinations of feedstocks in making compost, and we established routines and protocols for conducting self-heating tests that will be used for future trials.

We proved that various materials of seaweed will produce heat in Dewar flasks when mixed with appropriate bulking materials, even if these materials may have high salinity and/or a very high pH.

We proved that a turning and mixing of the content in the flasks may initiate a new round of heating.

We saw that the ambient temperature affects the heat development and that a small-sized insulated compost tumbler will require ambient temperatures well above 20 °C (or a much better insulated vessel) to demonstrate temperature dynamics comparable with the same substrates in a Dewar flask.

We saw that high-N algae fiber, despite a low concentration of mineral N, may initiate substantial self-heating when Leca is applied as a bulking agent and that a ratio of 1:3 (Leca-fiber) gave more heat than 3:1 in Dewar flasks. However, we also saw that it is not straightforward to transfer such values to other composting conditions, since the 1:3 ratio did not give successful composting in an insulated tumbler.

We saw that algae fiber may comprise a significant proportion of substrate in a windrow compost, where thermophilic conditions were achieved for short periods. Further studies are required to study how this composting has affected the suitability of the algae fiber as a fertilizer/soil amendment, or as a raw material for making compost extracts for biostimulants.

6 References

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