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Suitability of Residues from Seaweed and Fish Processing for Composting and as Fertilizer

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Abstract: There is a need to find novel sources of fertilizers to meet the increasing food demands of a growing human population and alternatives to mined and synthetic fertilizers for the certified organic sector. Composting is a common method for processing and stabilizing organic residues for use in horticulture. To that end, a small-scale composting experiment with six combinations of dried and ground rockweed (*Ascophyllum nodosum*), algae fiber from chemically processed rockweed, ground bones and fishmeal from cod (*Gadus morhua*), and ground blue mussels (*Mytilus edulis*) was conducted in Dewar flasks to assess whether these residues are suitable for composting and have potential for use as fertilizers. Expanded clay aggregates were used as a bulking material. Physicochemical analyses were performed on the residues and their mixtures before and after composting, and the temperature in the flasks was monitored for 92 days. Suitability was determined by evaluating the temperature dynamics, changes in physiochemical parameters, and nutrient profiles. All treatments generated heat, with reductions in C/N ratio, weight, and volume, demonstrating suitability for composting. The treatments with algae fiber had a higher mean temperature (34.5 vs. 29.0 °C) and more degree days above the thermophilic range (mean = 176- vs. 19-degree days), the greatest reduction in volume (mean = 35% vs. 27%), and the lowest C/N ratios at the end of active composting (18 vs. 24) compared to the treatments with dried and ground seaweed. In terms of fertilizer value, none of the finished composts were balanced for use as fertilizers alone and, in some cases, contained too much Na, but contained sufficient concentrations of K, S, Mg, and Ca and could be a valuable source of these nutrients and organic matter in combination with other N- and P-rich sources.

Keywords: compost; marine biomass stabilization and conversion; thermodynamics; organic fertilizer; plant nutrients; composting degree days; electrical conductivity

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1. Introduction

A growing human population will need more food, and for food production to be sustained into the future, it must be produced in a way that not only does less harm to the resource base, but ideally improves it [1–4]. Soil that contains a high amount of organic matter is more capable of handling ongoing and future climatic changes and is more productive [5,6]. One way to increase the organic matter content of soils is to add compost [7,8]. While there are numerous sources of raw material for composting already available, one source that has enormous potential yet is currently underutilized is the ocean [9–11].

Coastal communities around the world have been using marine-based fertilizers for centuries, if not millennia [12]. In some cases, these resources were exported and became important commercial products. One example is the export of fish-based "guano" from Norway, which was a common industry until the Second World War (Fiskehoder på østsiden av Skagen, 1930-tallet-Vardø Museum/DigitaltMuseum). Even today, a number of fertilizers, soil amendments, and biostimulants based on marine raw materials are available on the market. These include fish hydrolysates and emulsions, seaweed extracts, and others [9,10,13], many of which have been approved for use in certified organic agriculture [14].

However, this industry is still small relative to the scale of the conventional fertilizer industry, both in volume and turnover. It is also small relative to the need for nutrients in agriculture, particularly the certified organic sector, in which conventional mineral fertilizers are restricted. Marine-derived fertilizers may be especially relevant for certified organic farming, but they also have potential for conventional agriculture. Farmers are becoming increasingly aware of the need to amend the soil with organic materials, and with the rising costs of energy and mineral extraction, recycled fertilizers may compete economically with fossil-derived materials in the future.

It is estimated that fisheries generate 29–64 million tons of residues annually [10], with the harvesting and processing of macroalgae (seaweed and kelp) reaching at least 17.5 million tons [13]. Residuals from fisheries, as well as the harvesting and processing of macroalgae, such as fish offcuts, bycatch, seaweed extraction residues, stipes, and fronds, can contribute to meeting the world's demand for plant nutrients. Marine residues are not only a source of macro- and micronutrients, but also of organic compounds such as amino acids, phytohormones, phenolic compounds, and polysaccharides, which may have a positive effect on soil and plant health [15–21].

Marine residues, however, are often produced far from agricultural areas and must be processed for stability and transportability. Composting may be a low-cost method for stabilizing organic residues and is commonly used for biosolids, farmyard manure, and garden residues. Composting is the aerobic decomposition of organic materials by thermophilic microorganisms under controlled conditions [22]. During composting, readily available carbon (C), nitrogen (N), oxygen (O), and water are converted into energy, cell structures, metabolites, and other biological compounds. Composting reduces the volume of organic residuals and can be an effective method for reducing the pathogen load [23], the amount of weed seeds [24,25], and breaking down pollutants in contaminated feedstocks [26]. It also accelerates the synthesis of certain compounds, such as humic acid, that may support soil and plant health [27], while concurrently acting as a source of beneficial soil microorganisms and semi-stable carbon [28]. Residues of marine origin are less commonly applied as compost feedstocks, but have been studied extensively for this purpose [18,29–36].

A successful composting process depends on three primary parameters: moisture content (MC), carbon-to-nitrogen (C/N) ratio, and access to oxygen (pore space) [22,37–39]. Composting can be performed successfully within a wide range of these parameters. A reasonable MC is in the range of 40–65% by weight (optimally 50–60%), the C/N should be 20–60 (optimally 25–40), and an acceptable oxygen concentration within the pore spaces is 5% (optimally >10%). This is provided by a bulking agent that creates pore spaces within the compost matrix. This bulking material should have a large (up to 50 mm) and varied particle size, be stable, and preferably have a large specific surface area. Wood chips and tree bark are commonly used as bulking agents in compost. The pore space can be determined by the bulk density (BD) of the material, which should be <700 kg $\cdot$ m^{-3} (optimally 400–600 kg $\cdot$ m^{-3}). pH is also important and should be between 6 and 9, but successful composting can be achieved outside of this range [38].

Composting generally goes through four phases defined by temperature and the composition of microorganism populations [37]. When feedstocks are first mixed, there is an initial mesophilic phase, with temperatures in the range of 20–45 °C, in which colonizing

microorganisms consume the most easily degradable sugars and amino acids. Their metabolic activities eventually raise the temperature into the thermophilic range (45–65 °C), at which point, another assemblage of microorganisms takes over. The thermophilic phase is the active phase during which pathogens and weeds are destroyed. It is also when most respiration, mineralization, and volatilization occur. CO_2 and H_2O are lost through respiration and evaporation, and N compounds undergo ammonification, nitrification, and denitrification [37,40]. Sulfur (S) can also be volatilized during the thermophilic phase [41]. The thermophilic phase is followed by a second mesophilic phase, called the "cool-down" phase, in which fungi dominate and degrade cellulose, hemicellulose, and lignin. Eventually, this transitions into the maturing phase, in which organic acids and phytotoxins are degraded and much of the remaining N is mineralized.

In the present study, a selection of marine residues available in Norway, consisting of a byproduct from the processing of the brown algae rockweed (*Ascophyllum nodosum*), fishmeal and dried head bones from fish in the cod family (Gadidae), and blue mussels (*Mytilus edulis*), were composted. Rockweed grows in coastal areas in the mid-littoral zone on both sides of the North Atlantic, from Portugal in the east to Greenland in the north and across to northeastern North America [12,42,43]. It is used in many products, including as a raw material for alginate, biopolymers, fertilizers, and biostimulants, and as a feed additive for livestock and pets [21,44]. We used dried and ground rockweed, sold as a feed additive, as well as a residual algae fiber material that resulted from processing dried rockweed into various fertilizer and biostimulant products with an extraction process using different inorganic acids and alkalis [21,43,45]. The dried and ground rockweed, while not residues, were included for comparison, since they represent rockweed in an almost natural state.

The fishmeal originated from facilities that process captured white fish from the cod family into salt cod or other products. Fishbone material also originates from this industry, which generates significant volumes of poorly utilized residues, consisting of backbones, heads, viscera, and entrails, that remain after dressing and fileting. Some processing facilities must also dispose of by-catch or fish that do not meet size or quality standards. These residues can be ground and hydrolyzed with formic acid. Lipids and soluble proteins can be recovered and used as feed. The remaining sediment is rich in N, phosphorus (P), and calcium (Ca) [46] and has demonstrated interesting fertilizer effects in previous studies [47,48]. The blue mussel is a common bivalve mollusk that lives in the intertidal zone on both sides of the North Atlantic. It is harvested wild or raised in aquaculture facilities in coastal regions.

While rockweed material contains significant potassium (K), magnesium (Mg), and S, fish and mussels contain N, P, and Ca. Combined, the materials may become a complete fertilizer for crop plants. Composting could be a simple and low-cost option for blending locally available marine-derived materials while stabilizing their nutrients and organic matter to produce a fertilizer, soil amendment, or growing medium.

With this background, the objectives of this study were to determine if achieving thermophilic composting (>45 °C) with readily available marine residues was possible and identify the combination that performed best based on the temperature profile (mean and degree days), degradation of organic matter (reductions in organic matter, as measured by reductions in loss on ignition (LOI) and volume), and decrease in the C/N ratio. We also assessed the nutrient compositions of the finished composts for their potential as fertilizers for crop plants.

2. Materials and Methods

2.1. Compost Feedstocks

The five feedstocks applied in the experiment were divided into carbon-rich and nitrogen-rich categories. The two seaweed products were used as the carbon sources, and the three fish and mussel residues were the nitrogen sources. A total of six treatments were created from combinations of these five feedstocks. Three were made with dried and ground seaweed (GS) as the carbon source, which had the consistency of wheat bran, a

dry matter (DM) content of 89 g · 100 g^{-1}, a particle size of <2 mm, a C/N ratio of 40, and total N and K concentrations of 1.4 and 1.9 g · 100 g^{-1} DM (Table 1). The other three treatments used the algae fiber (AF) residue as the carbon source. This remained after industrial extraction with potassium hydroxide (KOH) from the dried and ground seaweed and had the consistency of wet clay, a DM content of 30 g · 100 g^{-1} (prior to drying for the experiment), a C/N ratio of 69, and total N and K contents of 0.5 and 8 g · 100 g^{-1} DM. Both of these feedstocks were delivered by Algea AS in Kristiansund, Norway.

Table 1. Characterization of feedstocks.

	Unit	GS	AF	FB	FM	MU
Dry matter (after drying and milling) [1]	g · 100 g^{-1}	89	90	95	90	98
Loss on ignition [1]	g · 100 g^{-1} DM	67	57	34	65	16
pH (1:5) [2]		5.6	9.5	7.0	6.3	7.2
Electrical conductivity (1:5) [2]	dS · m^{-1}	15.26	13.78	16.80	10.86	8.84
Total carbon [2]	g · 100 g^{-1} DM	37.7	35.8	15.4	35.3	15.2
Total organic carbon [3]	g · 100 g^{-1} DM	32	28	14	30	8
% total organic carbon of total carbon	%	84	78	93	86	53
Total nitrogen [2]	g · 100 g^{-1} DM	0.94	0.52	4.83	9.97	1.44
C/N		40	69	3	4	11
P [3]	g · 100 g^{-1} DM	0.09	0.34	12.24	3.11	0.14
K [3]	g · 100 g^{-1} DM	1.86	5.02	0.14	5.21	0.31
S [3]	g · 100 g^{-1} DM	2.75	0.86	0.27	0.89	0.37
Ca [3]	g · 100 g^{-1} DM	1.50	9.78	25.47	15.82	35.97
Mg [3]	g · 100 g^{-1} DM	0.80	1.38	0.33	1.51	0.16
Na [3]	g · 100 g^{-1} DM	3.26	1.22	0.52	1.38	0.98

GS = ground seaweed, AF = algae fiber, FB = fishbone, FM = fishmeal, and MU = mussel. Results for EC are based on an extraction ratio of 1:10 compost/deionized water (*v*/*v*), which were multiplied by two to make them comparable to the standard ratio of 1:5. [1] Determined at the Norwegian Centre for Organic Agriculture. [2] Determined at the Norwegian University of Life Sciences. [3] Determined at the Aristotle University of Thessaloniki.

The three nitrogen-rich feedstocks were cod (*Gadus morhua*) head bones (FBs), fishmeal made of cod (FM), and blue mussels (MUs). Pure FBs were selected instead of bone-rich acidified sediment (described in the introduction) to obtain a well-defined material. The FBs were first subject to enzymatic hydrolysis, rinsed thoroughly in fresh water, and kept frozen until drying and milling [46]. The FB material was provided by SINTEF Ocean in Trondheim, Norway. The FM was a residue from salt cod production and consisted of whole cod that were too small for fileting. They were processed in a large, rotating dryer that turned the flesh into a fine powder. The powder was sieved off for use as a protein source. The remaining aggregates, composed of bones and attached flesh, were used in this study. This material was provided by Bluecirc AS in Kristiansund, Norway. The MU residues used in this study consisted of small and damaged mussels and small amounts of byssus threads and algal growths that were left over after sorting and scrubbing at a commercial packing facility. They were kept frozen at −18 °C until drying and milling. The mussels were provided by Norgeskjell AS in Rissa, Norway.

As the bulking agent, we chose to use expanded clay aggregates (brand Leca®) with a diameter in the range of 4–10 mm. This material is inert and does not contribute C or N, which we wanted to derive exclusively from the sea. It is also porous and provides a large specific surface area for microorganisms to colonize. The clay aggregates were provided by Leca Norge AS in Rælingen, Norway.

The fresh AF was stored at 4 °C in an airtight bag, and FBs and MUs were stored frozen (−18 °C) until all three were dried at 55 °C and milled with a hammer mill into a fine powder. The powders were stored in airtight containers in a cool, dark room until the start of the experiment. The GS and FM were already dried and ground by the manufacturers. The FM was further sieved to a particle size of <2 mm to remove the large aggregates and

transferred to an airtight container. The GS was stored in its original packaging and was not subject to any additional pre-treatment. The Leca® aggregates were sieved to remove particles < 4 and >10 mm in diameter, washed with tap water, and dried. All analyses on the feedstocks were performed after pre-treatment.

2.2. Experimental Design

To test the suitability of the marine feedstocks for composting, we applied a small-scale self-heating test, based on the "Rottegrad" scale classification system, which is a method commonly used for determining compost stability or maturity [49–52]. As normally practiced, the method consists of filling Dewar flasks (well-insulated vacuum flasks) with moistened compost, placing them in a room at 20 °C, and monitoring the temperature inside the flask at a height of 5 cm above the bottom. In this study, we used a model 16C from KGW-Isotherm GmbH (Karlsruhe, Germany), which has a 100 mm diameter opening and a volume of 2075 mL (to the rim). The degree of maturity is assessed using a scale that compares the temperature in the flask relative to room temperature (20 °C is standard), or alternatively, is based on the absolute temperature within the flask. However, the self-heating method can also be used to test the potential suitability for composting fresh feedstocks and to screen raw materials and mixtures before scaling up [52,53].

The treatments were created by combining one carbon source with one of each type of nitrogen source for a total of six treatments. All treatments were performed in triplicate, resulting in a total of 18 Dewar flasks. The feedstock amounts in the six treatments were determined using an Excel-based compost recipe calculator developed by Agrilab Technologies, LLC (Enosburg Falls, VT, USA). The MC, concentrations of C and N (% of DM), BD, and weight of each feedstock were entered into the spreadsheet. Based on this information, the C/N ratio, BD, MC, weight, and volume of the total mix were calculated. These parameters were adjusted by changing the weights of the individual feedstocks in the calculator. We aimed for a C/N ratio of 25, an MC of 65%, and a BD of approximately 750 g $\cdot$ L^{-1} in all treatments. This BD is somewhat higher than optimal, but this was intentional, since compaction at the lab scale is not as great a challenge as it is in full-scale composting.

The organic feedstocks and water were weighed in the amounts determined by the compost recipe calculator (Table 2). The Leca® was measured by volume. The dry organic feedstocks were blended before adding the water and the Leca®. Each treatment was mixed in bulk and the material for the three replicates was taken from this mixture. Samples of the remaining mixtures were frozen in airtight containers until further analysis. All flasks were first weighed empty (including the thermistor), then filled to the top with the mixture, and weighed again. During this filling, the flasks were carefully tapped five times on the palm of the hand twice—once after filling to 1/3 of the volume, and again after filling to 2/3. After topping off, each flask was covered with a lid made from compost fleece (cloth), the same kind used for covering compost windrows. This lid reduced moisture and heat loss while allowing for gas exchange. The weight of the contents (the full flask weight minus the empty flask weight) was calculated for the first of the three flasks for each treatment. The other two flasks (replicates) were filled with the same weight of material. The BD was calculated by dividing the weight of the contents by the volume in the flask. At the start of the experiment, all treatments had a volume of 2075 mL.

Each treatment was assigned a code that reflected which feedstocks were included in each treatment, e.g., GS + MU represents ground seaweed mixed with mussels (Table 2). A table in a climate-controlled room was divided into three blocks, further divided into plots, with one replicate flask from each treatment randomly assigned to a plot in one of the three blocks. A rotating table fan was used to ensure an even temperature in the room, which was heated by two electric ovens. The temperature in the room was monitored (Scanntronik Mugrauer GmbH, Zorneding, Germany) and varied between 17 and 23 °C during the experiment (mean = 20.1 °C).

Table 2. Amounts (g per batch, except for Leca®, 2 L of which was applied per batch) of substrates applied in each of six mixtures of marine feedstocks for composting, with the sum of sample material removed on two occasions (g per batch).

Treatment Code	C-Rich Feedstock (AF or GS)	N-Rich Feedstock (FB, FM, or MU)	Ratio of Feedstocks	Water	Leca®	Total		Weight of Sample Removed
	g	g		g	L	g	L	g
AF + FB	1900	365	5:1	3430	2.0	6270	8.27	85
AF + FM	2000	195	10:1	3268	2.0	6017	7.97	84
AF + MU	1400	880	2:1	3655	2.0	6505	8.21	107
GS + FB	2000	100	20:1	3236	2.0	5892	8.01	87
GS + FM	2100	53	40:1	3304	2.0	6027	8.21	91
GS + MU	1900	310	6:1	3471	2.0	6261	8.35	86

AF = algae fiber, GS = ground seaweed, FB = fishbone, FM = fishmeal, and MU = mussel.

As with composting on a large scale, the material in the flasks was "turned" periodically. This was performed when the temperature in all flasks dropped below 35 °C or was declining. To simulate the turning of real compost, each flask was emptied into a container, the material was well mixed by hand, and was then refilled. Before emptying, the volume of the contents was estimated by measuring the distance from the rim of the flask to the top of the contents at four points per flask, after which, the flasks were weighed. A 100 mL sample was removed from each flask and weighed. The weight of the sample was subtracted from the weight of each flask. Samples taken during composting were left to dry at room temperature until analysis, including the measurement of DM. Samples taken upon the completion of the composting were oven-dried at 55 °C.

The feedstocks were mixed and the flasks were filled on 1 February 2023 (day 1). They were turned on day 31 (end of phase one), day 62 (end of phase two), and emptied on day 92 (end of phase three). At this point, the contents of the flasks were transferred to plastic buckets, covered with a compost cloth, and left to mature at ambient temperature (12–20 °C) for one month. After this maturation period, the buckets were sealed and placed in storage.

The temperature in each flask was monitored with an NTC thermistor (Thermofox Universal, Scanntronik Mugrauer GmbH, Zorneding, Germany) and logged hourly. The logger sent the data every 24 h.

2.3. Physical and Chemical Characterization

Analyses were conducted at three different laboratories (Table 1). Measurements of the DM and LOI in the feedstocks, start mixes, and finished compost (all replicates) were conducted at the Norwegian Centre for Organic Agriculture (NORSØK) in Tingvoll, Norway. Determination of the total C and total N in the feedstocks, start mixes, and finished composts (all replicates) and determination of the pH and EC in the feedstocks (all replicates), start mixes, and finished compost (all replicates) were performed at the Norwegian University of Life Sciences (NMBU) in Ås, Norway. The nutrient content used for evaluating the fertilizer value of the compost and total organic carbon (TOC) were determined at the Aristotle University of Thessaloniki (AUTh) in Greece. These analyses were conducted on the feedstocks and samples from two of the three replicates taken during the first turning and from the finished compost.

To determine the DM and LOI, the samples were dried at 105 °C until reaching a stable weight and ignited at 550 °C for 180 min. Prior to the remaining analyses, Leca aggregates were removed, and then the remaining sample material was milled with an electric mortar and pestle (RM200, Retsch GmbH, Haan, Germany) for three minutes. For the pH and EC analysis, the samples were mixed at a ratio of 1:5 (v/v) of compost/deionized water and left to stand overnight. A subsample of 2 mL of this mixture was then further diluted with 2 mL of deionized water to provide enough free liquid for the EC measurements.

This resulted in a mixture ratio of 1:10. The results for EC were multiplied by two to make them comparable to the standard 1:5 mixture ratio. The pH was determined by a MeterLab PHM210 (Radiometer Medical ApS, Brønshøj, Denmark) and the EC by a 712 Conductometer (Metrohm AG, Herisau, Switzerland). At NMBU, the total C was determined in crushed samples by dry combustion [54] at 1050 °C using a Leco CHN TrueSpec 628 instrument (St. Joseph, MI, USA). The total N was measured on the same instrument according to the Dumas method [55].

At AUTh, a CN elemental analyzer (Leco Truspec, St. Joseph, MI, USA) was employed for the analysis of the total carbon content and total nitrogen content, with EDTA as a standard. The TOC was determined after the removal of calcium carbonate with 37% hydrochloric acid. The concentrations of total P, K, Mg, Ca, and S were measured after digestion in nitric acid and hydrogen peroxide, and determined by ICP-OES (5110ICP-OES, Agilent Technologies, Santa Clara, CA, USA).

2.4. Statistical Analysis

For statistical analysis, the treatments were grouped by carbon source (n = 2), nitrogen source (n = 3), treatment (n = 6), and phase (start/finish and the three phases) as fixed factors in the variance analysis. The response variables were the temperature in the flasks, C/N ratio, moisture content, weight, volume, bulk density, total C, total N, dry matter content, loss-on-ignition, pH, and electrical conductivity for evaluating the composting process and total C, total N, P, K, S, Ca, Mg, and Na for evaluating the fertilizer potential. For the analyses related to the fertilizer potential, statistically significant differences between the treatments were harder to obtain, because samples from only two of the three replicates were analyzed. For temperature data, the means for the entire composting trial and for each phase were analyzed, as well as the total values for the degree days. For other characteristics, we evaluated the differences between the initial values and the values at the finish. Since the initial values differed more between treatments than we aimed for, the relative changes per treatment in percentage were applied as the response variables. For pH, the change from the start to the finish was calculated using the percentage difference in the concentration of H^+ ions. For the moisture content and other values that were percentages or ratios, it is not correct to calculate the percentage change, but this was performed here for illustrative purposes. Also, for the C/N ratio, a relative percentage change is not optimal, but was included to handle all data in a similar way. Statistical analyses were conducted using software from Minitab, LLC (version 21.4.3, State College, PA, USA). The statistical models applied included Pearson correlation, Linear Regression, and one-way ANOVA with post hoc Tukey tests and 95% confidence intervals. For the variance analysis (ANOVA), the model applied was $y_{ij} = \mu_i + \epsilon_{ij} \ldots$, where y_{ij} is the jth observation of the response for the ith factor level, μ_i is the true mean of observations at the ith factor level, and ϵ_{ij} is the error that is independently and normally distributed with a mean of 0 and constant variance σ^2. The hypothesis test for the one-way analysis used the formula H_0: $\mu_1 = \mu_2 = \ldots = \mu_r$ and H_1: at least one mean is not equal to the others. Statistically significant differences were assigned to p-values of < 0.05. Tables and figures were made using Minitab, Python (version 3.11.5), and Excel (Microsoft® Excel® for Microsoft 365 MSO version 2407 Build 16.0.17830.20166 64-biters).

3. Result

3.1. Temperature

The temperature data are presented in two ways. First, as 24 h means per treatment for each phase and the entire experiment, and further as degree days [56]. Degree days were calculated as the 24 h mean of each treatment per day minus a base temperature ($T_{24\text{-}h\ mean} - T_{Base}$), summated over the whole experimental period. We applied three base temperatures: room temperature (base = 17–23 °C); thermophilic temperature (base = 45 °C); and hygienization temperature (base = 55 °C). Any 24 h average degree day below these base temperatures was then set to 0. These base temperatures were used to

compute the degree days above room temperature (RDDs), degree days above thermophilic temperature (TDDs), and degree days above hygienization temperature (HDDs).

The mean temperatures over the whole 92-day measurement period (MT_t) varied between 28.6 and 37.0 °C and were significantly higher in the treatments where algae fiber was the carbon-rich feedstock (Table 3). AF + FM had the highest MT_t (37.0 °C), followed by AF + FB (34.0 °C). GS + FB and GS + FM had the lowest MT_t (28.6 and 28.7 °C, respectively). The AF treatments with FM or FB maintained higher temperatures over time than the other treatments, particularly in the first phase. The other treatments exhibited sharp peaks after which the temperature declined quickly (Figure 1). The time required to reach the peak temperature varied between treatments. The temperature increased rapidly in AF + FM and AF + FB, which were already in the thermophilic range (>45 °C) on days four and five. These treatments also reached the thermophilic range after the first turning. AF + MU did not reach the thermophilic range during the first phase, but did during the second. The temperature curves were more variable for the treatments with GS than those with AF. The GF treatments remained near ambient temperature for up to ten days or more after initiation (e.g., GS + FB, Figure 1). All three had at least one replicate that reached the thermophilic temperature range during the first phase, and GS + FM and GS + MU had peaks during the second phase, during which, some replicates reached thermophilic temperatures again. GS + FB stands out, as it saw its highest temperatures during the third phase and reached thermophilic temperatures when most other treatments approached ambient temperatures (Figure 1).

Table 3. Mean temperature (MT) for the duration of the composting experiment and each phase (MT_1 = 1st phase, MT_2 = 2nd phase, and MT_3 = 3rd phase); degree days above room temperature (RDDs); degree days above 45 °C (TDDs); and degree days above 55 °C (HDDs). Within each temperature category, statistically significant differences between treatments, i.e., combinations of feedstocks, are shown by capital letters A, B, C, etc., and standard error is given.

Treatment	MT_t °C	MT_1 °C	MT_2 °C	MT_3 °C	RDD >20 °C	TDD >45 °C	HDD >55 °C
AF + FB	$34.0^{AB} \pm 1.0$	$46.1^{B} \pm 0.8$	$32.2^{AB} \pm 1.5$	$23.7^{A} \pm 1.2$	$1262^{AB} \pm 92.1$	$178^{B} \pm 19.7$	$12^{AB} \pm 1.9$
AF + FM	$37.0^{A} \pm 1.5$	$51.7^{A} \pm 0.9$	$32.8^{AB} \pm 1.7$	$26.6^{A} \pm 2.1$	$1529^{A} \pm 128$	$283^{A} \pm 22.6$	$41^{A} \pm 17.0$
AF + MU	$32.5^{ABC} \pm 1.8$	$29.5^{C} \pm 0.9$	$39.1^{A} \pm 2.2$	$28.9^{A} \pm 2.5$	$1148^{ABC} \pm 166$	$68^{C} \pm 22.1$	$5^{B} \pm 5.0$
GS + FB	$28.7^{C} \pm 0.3$	$30.7^{C} \pm 0.1$	$24.8^{C} \pm 0.8$	$30.7^{A} \pm 0.2$	$781^{C} \pm 31.4$	$23^{C} \pm 5.8$	$0^{B} \pm 0$
GS + FM	$28.6^{C} \pm 0.2$	$29.8^{C} \pm 0.2$	$29.3^{BC} \pm 1.7$	$26.5^{A} \pm 1.2$	$780^{C} \pm 21.6$	$1^{C} \pm 0.8$	$0^{B} \pm 0$
GS + MU	$29.7^{BC} \pm 0.8$	$31.9^{C} \pm 2.1$	$32.4^{AB} \pm 0.6$	$24.8^{A} \pm 0.1$	$884^{BC} \pm 69.5$	$32^{C} \pm 31.9$	$1^{B} \pm 0.6$

AF = algae fiber, GS = ground seaweed, FB = fishbone, FM = fishmeal, and MU = mussel.

The values for degree days above room temperature (RDDs, Table 3) showed the same pattern as the total mean temperatures. Algae fiber with fishmeal (AF + FM) had a twice as high accumulated heat above room temperature (1529) than ground seaweed with fishmeal (GS + FM), which had 780 RDDs. AF + FM and AF + FB had significantly more TDDs (>45 °C) than all the other treatments. Likewise, only these treatments reached a substantial amount of HDDs (>55 °C), with AF + FM reaching the most (41). EU standards require that the temperature in compost with animal by-products is maintained above 55 °C for at least 14 days [57]. In the United States, the requirement for composting animal by-products is three days above 55 °C for an in-vessel or static aerated pile system and 15 days (including turning five times) in a windrow system [58].

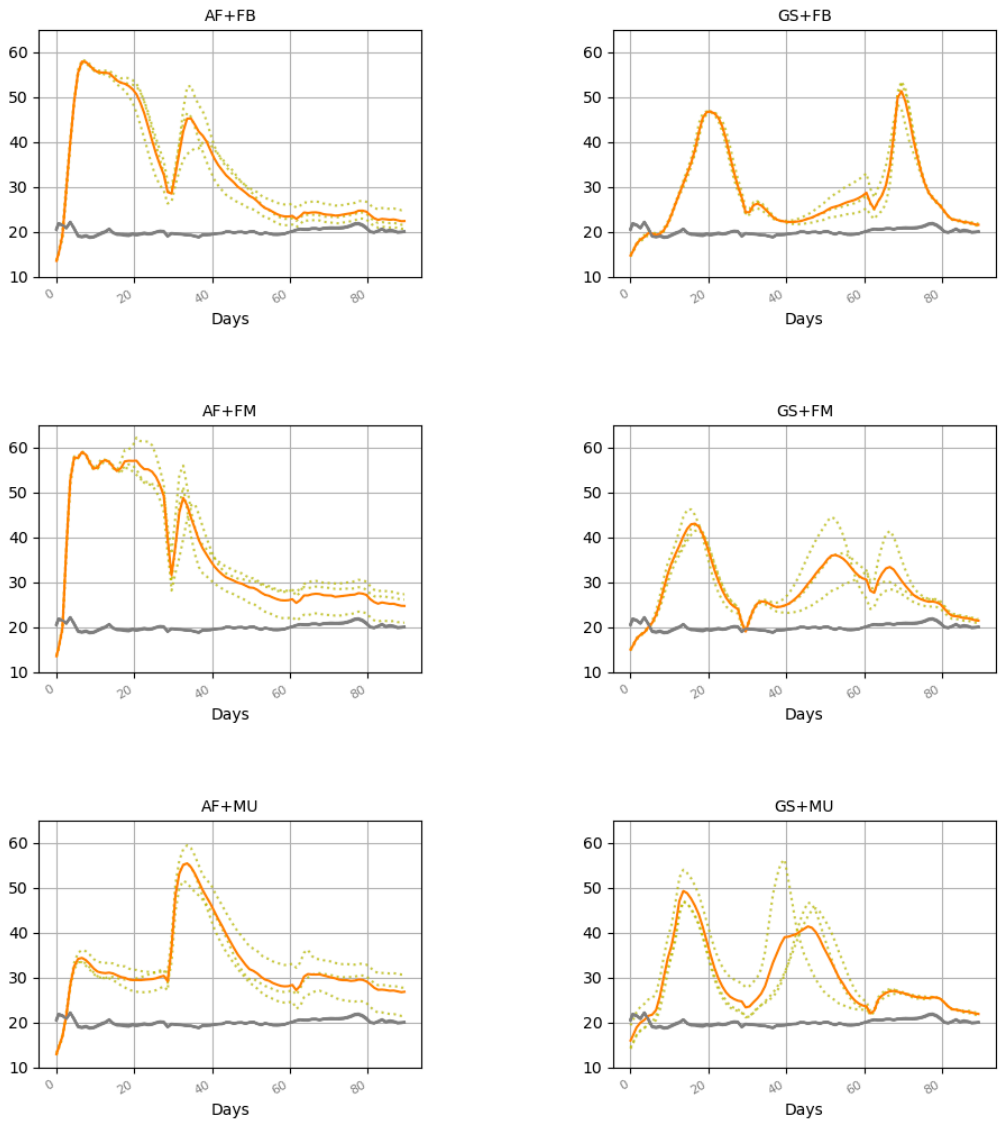


Figure 1. Temperature in the Dewar flasks for each treatment and the room temperature across the whole experimental period (92 days). Solid orange lines represent the mean temperatures, dashed lines show the three replicate values, and solid gray lines show room temperature. Flasks were emptied, contents mixed, and flasks refilled on days 31 and 62.

3.2. Physical and Chemical Characterization and Changes

At the start of the experiment, the treatments with AF had C/N ratios between 24 and 28, whereas the GS treatments had C/N ratios of 30–34 (Table 4). The mean MC varied little and was approximately 65% for all treatments (SD = 0.74), as we had aimed for. The BD was somewhat lower than what we aimed for. In the AF treatments, the BD varied from 617 to 769 g · L^{-1}, whereas the GS treatments had a BD between 573 and 624 g · L^{-1}.

In all treatments, the MC, LOI, weight, volume, BD, DM content/flask, H^+ ion concentration, total C concentration, and C/N ratio decreased during the experiment, whereas the concentration of total N increased (Table 4). This is expected during the thermophilic aerobic decomposition of organic materials. The EC increased for the AF treatments and decreased for the GS treatments.

Table 4. Chemical and physical characteristics of the treatments at the start (S), the finished composts (F), and percentage change (%Δ) between start and finish. For changes within each characteristic, statistically significant differences between treatments, i.e., combinations of feedstocks, are shown by capital letters A, B, C, etc. Standard error is given for finished compost and changes.

Characteristic	Unit		AF + FB	AF + FM	AF + MU	GS + FB	GS + FM	GS + MU
Moisture content	% weight	S	64.0	63.4	64.7	65.3	65.5	64.4
		F	41.7 ± 1.4	37.2 ± 0.7	47.1 ± 0.0	51.6 ± 0.2	51.5 ± 1.0	50.0 ± 1.4
		%Δ	**−35 ^{B} ± 2.1**	**−41 ^{B} ± 1.1**	**−27 ^{A} ± 0.1**	**−21 ^{A} ± 0.3**	**−21 ^{A} ± 1.5**	**−22 ^{A} ± 2.1**
Loss on ignition	g · 100 g^{-1} DM	S	52.3	58.5	40.9	75.6	77.9	67.5
		F	31.3 ± 0.2	42.8 ± 0.7	15.4 ± 0.7	65.5 ± 1.3	64.7 ± 1.1	52.0 ± 1.1
		%Δ	**−40 ^{D} ± 0.4**	**−27 ^{C} ± 1.1**	**−62 ^{E} ± 1.5**	**−14 ^{A} ± 1.7**	**−17 ^{AB} ± 1.4**	**−23 ^{BC} ± 1.7**
Weight of flask contents	g	S	1325	1280	1595	1260	1190	1295
		F	670 ± 12.6	592 ± 8.3	930 ± 21.8	755 ± 5.8	695 ± 2.9	797 ± 6.7
		%Δ	**−49 ^{B} ± 1.0**	**−54 ^{C} ± 0.7**	**−42 ^{A} ± 1.4**	**−40 ^{A} ± 0.5**	**−42 ^{A} ± 0.2**	**−39 ^{A} ± 0.5**
Volume of flask contents	ml	S	2075	2075	2075	2075	2075	2075
		F	1296 ± 19.7	1200 ± 19.8	1568 ± 24.0	1508 ± 36.4	1438 ± 9.4	1595 ± 12.9
		%Δ	**−38 ^{C} ± 1.0**	**−42 ^{C} ± 1.0**	**−24 ^{A} ± 1.2**	**−27 ^{AB} ± 1.8**	**−31 ^{B} ± 0.5**	**−23 ^{A} ± 0.6**
Bulk density	g · L^{-1}	S	639	617	769	607	573	624
		F	517 ± 2.5	493 ± 3.4	593 ± 5.6	501 ± 9.0	483 ± 3.7	499 ± 5.7
		%Δ	**−19 ^{ABC} ± 0.4**	**−20 ^{BC} ± 0.6**	**−23 ^{C} ± 0.7**	**−18 ^{AB} ± 1.5**	**−16 ^{A} ± 0.6**	**−20 ^{BC} ± 0.9**
DM content/flask	g	S	477	469	563	437	411	461
		F	391 ± 2.9	372 ± 4.3	492 ± 11.9	366 ± 1.4	337 ± 5.4	398 ± 7.5
		%Δ	**−18 ^{AB} ± 0.6**	**−21 ^{B} ± 0.9**	**−13 ^{A} ± 2.1**	**−16 ^{AB} ± 0.3**	**−18 ^{AB} ± 1.3**	**−14 ^{A} ± 1.6**
pH		S	9.45	9.61	9.43	6.60	6.62	6.97
		F	10.02 ± 0.02	10.10 ± 0.02	9.81 ± 0.02	6.98 ± 0.10	6.84 ± 0.01	8.16 ± 0.11
		%Δ [1]	**−73 ^{BC} ± 1.1**	**−68 ^{B} ± 1.8**	**−59 ^{AB} ± 2.3**	**−56 ^{AB} ± 10.4**	**−40 ^{A} ± 1.7**	**−93 ^{C} ± 1.8**
Electrical conductivity	dS · m^{-1}	S	11.00	12.78	11.62	11.02	11.28	11.08
		F	17.07 ± 0.15	17.43 ± 1.02	15.33 ± 0.46	9.23 ± 0.46	10.52 ± 0.87	9.85 ± 0.74
		%Δ	**55 ^{A} ± 1.4**	**36 ^{A} ± 8.0**	**32 ^{A} ± 4.0**	**−12 ^{B} ± 4.2**	**−7 ^{B} ± 7.7**	**−11 ^{B} ± 6.6**
Total C	g · 100 g^{-1} DM	S	32.2	36.0	26.9	36.7	36.8	34.4
		F	22.9 ± 0.4	26.8 ± 0.2	20.3 ± 0.2	33.5 ± 0.1	34.5 ± 0.3	29.5 ± 0.1
		%Δ	**−29 ^{D} ± 1.4**	**−26 ^{CD} ± 0.4**	**−24 ^{C} ± 1.0**	**−9 ^{A} ± 0.3**	**−6 ^{A} ± 0.8**	**−14 ^{B} ± 0.4**
Total N	g · 100 g^{-1} DM	S	1.33	1.34	0.96	1.20	1.22	1.00
		F	1.53 ± 0.01	1.54 ± 0.04	0.97 ± 0.01	1.41 ± 0.03	1.45 ± 0.03	1.26 ± 0.07
		%Δ	**15 ^{AB} ± 1.1**	**15 ^{AB} ± 3.0**	**1 ^{B} ± 0.6**	**29 ^{A} ± 2.6**	**19 ^{A} ± 2.6**	**26 ^{A} ± 6.9**
C/N		S	24	27	28	34	30	34
		F	15 ± 0.3	17 ± 0.5	21 ± 0.3	24 ± 0.4	24 ± 0.4	24 ± 1.3
		%Δ	**−38 ^{C} ± 1.1**	**−35 ^{C} ± 1.7**	**−25 ^{AB} ± 1.1**	**−29 ^{ABC} ± 1.3**	**−21 ^{A} ± 1.3**	**−31 ^{BC} ± 3.7**

AF = algae fiber; GS = ground seaweed; FB = fishbone; FM = fishmeal; and MU = mussel. [1] Calculated as percentage change in the concentration of H^+ ions.

AF + FM and AF + FB saw the greatest reductions in MC, with the final MCs being 37% and 42% of the weights (Table 4). This corresponds well with the heat generation being the highest in these treatments (Table 3). GS + FB and GS + FM had the highest MCs upon completion at a 52% weight. AF + FM, followed by AF + FB, also had significantly greater percentage reductions in weight (54% and 49%) than all of the other treatments, with GS + MU having the lowest reduction (39%). The reduction in volume followed the same pattern as the weight and MC, with the greatest reduction occurring for AF + FM (42%) and the lowest for GS + MU (23%).

MU had a much lower LOI than FB and FM due to the shells. With an LOI of only 16 g · 100 g^{-1} DM (Table 1), the proportion of ashes (minerals) was 84 g · 100 g^{-1} DM in MU compared to 66 g · 100 g^{-1} in FB and 35 g · 100 g^{-1} in FM. This explains the lower level of LOI for both MU treatments at the start and finish (Table 4). AF + MU saw a significantly greater reduction in LOI than the other treatments, meaning that it lost relatively more organic matter during composting, and in the end, had an LOI content of only 15.4 g · 100 g^{-1}.

BD was reduced over time in all treatments. AF + MU experienced the greatest mean reduction (23%). There was more overlap in the Tukey grouping than the other parameters (Table 4), but this may have also been due to the large variations in BD at the start. The reduction in the BD for the AF treatments was significantly greater than that for the GS

treatments, and treatments containing MU as the N source saw larger reductions in BD than those with FM.

The concentrations of total C decreased in all treatments, but much more for AF than for GS as the carbon source. Contrary to this, the concentration of total N increased in all treatments and relatively more for GS than AF. The C/N ratio was reduced from initially between 24 (AF + FB) and 34 (GS + FB and GS + MU) to between 15 (AF + FB) and 25 (for GS + FM). This was a reduction of 38% for AF + FB and 21% for GS + FM.

Due to alkaline treatment during extraction, the pH in the AF treatments was approximately 9.5 at the start and increased slightly to 9.8–10.1 at the end (Figure 2). For the GS treatments, the pH was between 6.5 and 7.0 at the beginning. After initially decreasing in these treatments, the pH increased towards the end to become somewhat higher than at the beginning (6.8–8.1). The pH in GS + MU increased significantly more than in all other treatments. The EC was similar for all treatments in the beginning (11.0–12.5 mS m^{-1}) and increased until the first turning, decreased until the second turning, especially in the GS treatments, and remained stable or increased again (only slightly for the GS treatments) towards the end of the experiment (Figure 3). There was a much greater spread of EC at the end than at the beginning, with the GS treatments having a value between 9.7 and 10.5 dS · m^{-1} (lower than at the start) and the AF treatments having one between 15.3 and 17.4 dS · m^{-1} (higher than at the start).

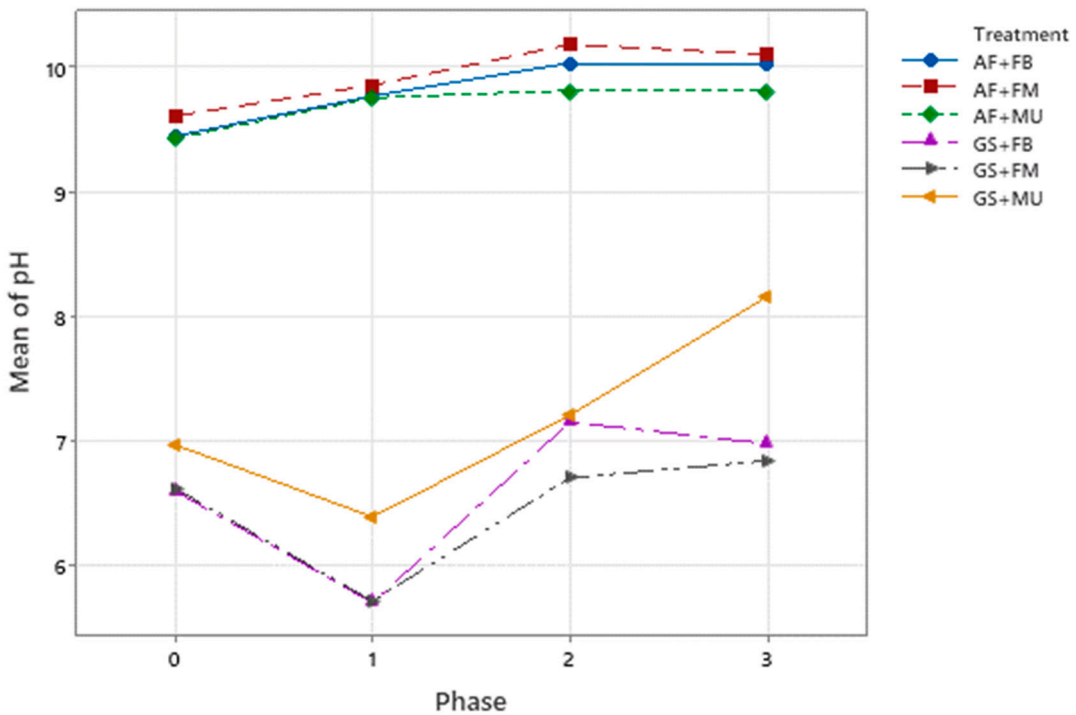


Figure 2. Mean pH per phase. Phase 0 = start mixes; phase 3 = completion of experiment.

The Pearson correlation test across all treatments showed a strong correlation between the concentration of total N at the start and the reduction in volume (r = 0.930), but not for the concentration of total C (r = 0.292, p = 0.241). A regression analysis across all treatments gave an r^2 (adj.) value of 85.7% for total N vs. reduction in volume. There was also a strong negative correlation between the percentage reduction in volume and TDDs (r = −0.835). Of all the start parameters (C/N, MC, and BD), MC correlated the most with temperature, particularly TDDs (r = 0.885), followed by C/N (r = −0.692). The lower the MC at the start, the greater the value of TDDs. There was a strong correlation (r = 0.807) for the percentage change in total C and RDDs, though it was weaker for the percentage change in total N and RDDs (r = 0.454, p = 0.06).

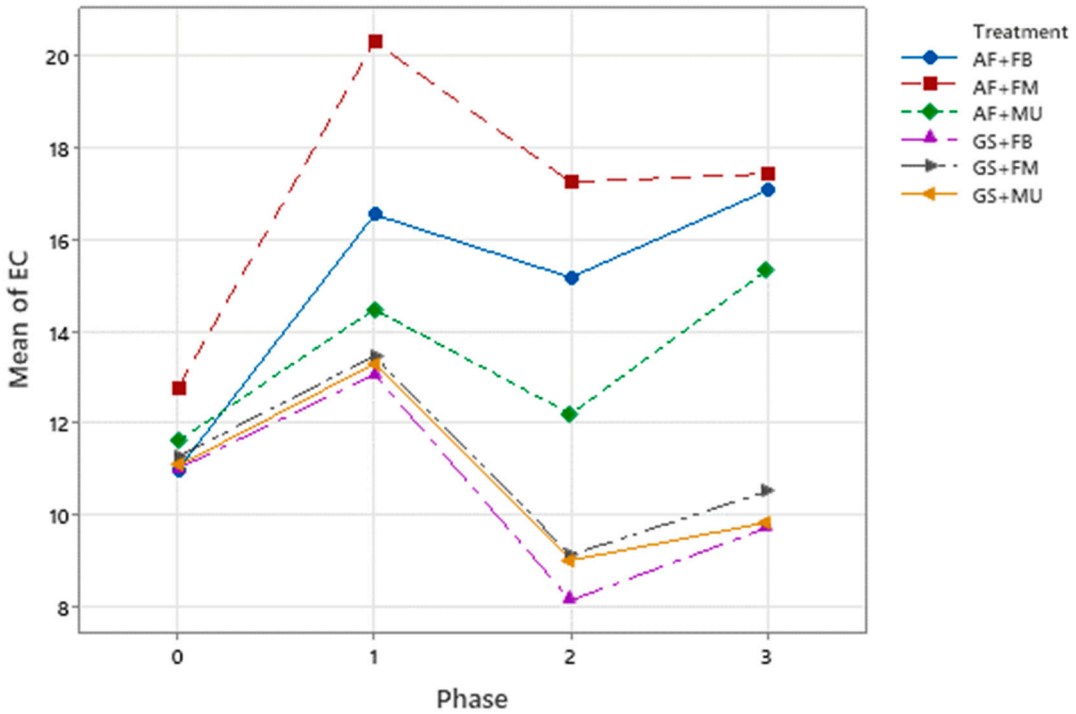


Figure 3. Mean EC per phase. Phase 0 = start mixes; phase 3 = completion of experiment.

3.3. Concentrations and Contents of Nutrients

Since the concentrations of nutrients are presented on a dry matter basis (g per 100 g DM), and the dry matter content (kg) in a material subject to composting was changed during the composting, we computed the contents of nutrients per flask and present these values in parallel to the concentrations in Table 5. The contents were computed as the concentration multiplied by the weight of dry matter per flask; hence, they use the unit of g per flask. For nutrients that are not converted to gas at temperatures found during composting, such as P and K, the content per flask should not change from the start to the end. Deviations are likely due to errors that are difficult to avoid, such as incorrect weighing, especially of material residues left in trays during turning, and the challenge of obtaining representative samples for the chemical analysis of heterogenous materials.

There were only small differences between the GS and the AF treatments in the concentration and content per flask of total C at the start (Table 5). By the end of the experiment, the GS treatments had higher concentrations, higher contents, and lower percentage reductions. With only two replicate measurements per treatment, statistically significant differences were not obtained. GS + FM had the highest concentration (35.3 g · 100 g^{-1}) and GS + FB had the highest content (123.3 g/flask) upon completion, whereas AF + MU had the lowest concentration of total C (20.4 g · 100 g^{-1}) and AF + FB had the lowest content (92.7 g/flask).

At the end of the experiment, the composts had a mean total N concentration between 0.83 g 100 · g^{-1} (AF + MU) and 1.35 g · 100 g^{-1} (AF + FM). The N content per flask was between 3.6 g/flask (GS + FM) and 5.0 g/flask (AF + FM). The concentrations of total N decreased relatively little compared with total C, as did the contents per flask, except in GS + FM, where the decrease in N content (25%) was similar to the decrease in C content. There was no clear distinction between the GS and AF treatments.

Table 5. Concentrations and contents of C, N, P, and K in the mixtures at the start of the study (S), in the finished compost (F), and the percentage change (%Δ).

Mineral	Unit		AF + FB	AF + FM	AF + MU	GS + FB	GS + FM	GS + MU
Total C	$g \cdot 100\ g^{-1}$ DM	S	33.6	37.2	29.7	37.5	38.4	35.1
		F	23.7	27.0	20.4	33.7	35.3	30.9
		%Δ	**−30**	**−27**	**−31**	**−10**	**−8**	**−12**
Total C	g/flask	S	160.4	174.2	167.1	163.8	157.9	161.9
		F	92.7	100.4	100.4	123.3	119.0	123.0
		%Δ	**−42**	**−42**	**−40**	**−25**	**−25**	**−24**
Total N	$g \cdot 100\ g^{-1}$ DM	S	1.34	1.33	0.86	1.12	1.17	0.99
		F	1.26	1.35	0.83	1.20	1.08	0.98
		%Δ	**−6**	**−1**	**−3**	**−7**	**−8**	**−1**
Total N	g/flask	S	6.4	6.3	4.8	4.9	4.8	4.6
		F	4.9	5.0	4.1	4.4	3.6	3.9
		%Δ	**−23**	**−19**	**−15**	**−10**	**−25**	**−15**
P	$g \cdot 100\ g^{-1}$ DM	S	2.48	0.59	0.27	0.70	0.18	0.10
		F	3.07	1.17	0.31	0.69	0.25	0.10
		%Δ	**24**	**98**	**16**	**−1**	**40**	**3**
P	g/flask	S	11.8	2.8	1.5	3.0	0.7	0.5
		F	11.8	4.0	1.5	2.5	0.8	0.4
		%Δ	**1**	**57**	**2**	**−17**	**15**	**−11**
K	$g \cdot 100\ g^{-1}$ DM	S	4.14	5.03	3.23	1.77	1.96	1.61
		F	5.36	6.15	3.66	2.31	2.43	2.22
		%Δ	**30**	**22**	**13**	**30**	**24**	**38**
K	g/flask	S	19.7	23.6	18.2	7.8	8.0	7.4
		F	21.0	23.0	18.0	8.5	8.2	8.8
		%Δ	**6**	**−3**	**−1**	**9**	**2**	**19**

AF = algae fiber; GS = ground seaweed; FB = fishbone; FM = fishmeal; and MU = mussels.

FB and FM had high P concentrations due to the bone content. This was reflected in the concentration of P in the start mixes, in the finished composts, and in the content of P per flask. The treatment with the highest concentration at the end of the experiment was AF + FB (3.07 $g \cdot 100\ g^{-1}$), followed by AF + FM and GS + FB (1.17 and 0.57 $g \cdot 100\ g^{-1}$). The lowest P concentrations were recorded in the two treatments with MU: 0.31 $g \cdot 100\ g^{-1}$ for AF + MU and 0.10 $g \cdot 100\ g^{-1}$ for GS + MU. The treatments with AF as the carbon source had higher concentrations of P. This was due to the higher C/N ratio of AF, which necessitated a greater proportion of nitrogen sources. There were also considerably higher concentrations of K in the AF treatments, which is explained by the treatment with KOH for alkalinization. AF + FM had the highest concentration at the end (6.15 $g \cdot 100\ g^{-1}$), followed by AF + FB (5.36 $g \cdot 100\ g^{-1}$). The lowest K concentration was in GS + MU (2.22 $g \cdot 100\ g^{-1}$). AF + FM had the highest content of K per flask (23.0 g) and GS + FM had the lowest (8.2 g). As expected, the contents of P and K per flask were quite stable, except for two deviations (AF + FM for P and GS + MU for K), which may be explained by sampling and/or weighing errors.

For S, the treatments with GS as the carbon source had higher concentrations and contents per flask before and after composting (Table 6). The GS treatments had greater and more positive percentage changes in the concentration and contents per flask, though the latter should not be possible. The highest concentration of S in a compost at the end of the experiment was observed in GS + FM (3.81 $g \cdot 100\ g^{-1}$) and the lowest was observed in AF + MU (0.71 $g \cdot 100\ g^{-1}$). For Ca, the AF treatments had higher concentrations and contents per flask than the GS treatments. The two treatments with MU stood out as having more Ca than the treatments with the other two nitrogen sources. The AF treatments also had more Mg than the GS treatments, both in concentration and content per flask. The highest Mg concentration and content at the end of the experiment was observed in

AF + FM (1.78 g · 100 g^{-1} and 6.6 g/flask). Both treatments with MU as the nitrogen source had the least Mg.

Table 6. Concentrations and contents of S, Ca, Mg, and Na in the mixtures at the start of the study (S), in the finished compost (F), and the percentage change (%Δ).

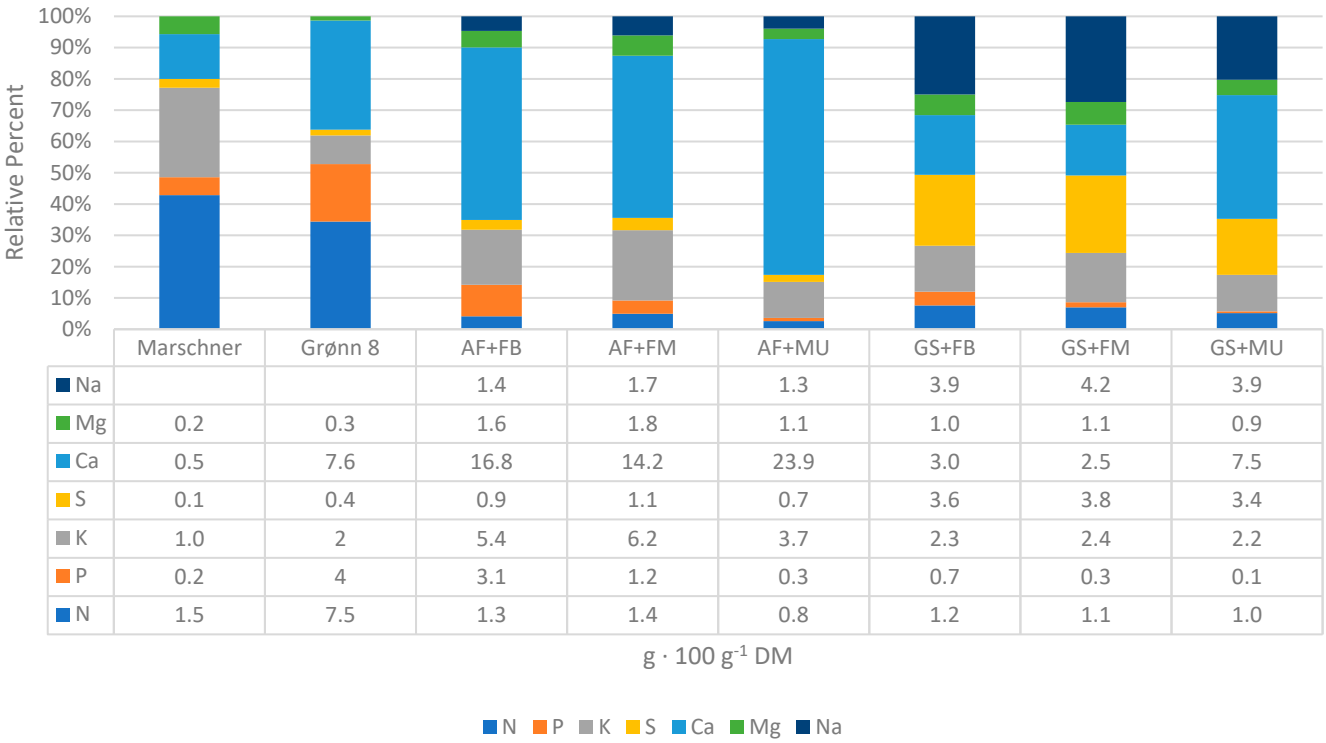
Mineral	Unit		AF + FB	AF + FM	AF + MU	GS + FB	GS + FM	GS + MU
S	g · 100 g^{-1} DM	S	0.75	0.86	0.67	2.63	2.69	2.37
		F	0.94	1.08	0.71	3.57	3.81	3.39
		%Δ	**25**	**25**	**6**	**36**	**41**	**43**
S	g/flask	S	3.6	4.0	3.8	11.5	11.1	10.9
		F	3.7	4.0	3.5	13.1	12.8	13.5
		%Δ	**2**	**−1**	**−8**	**14**	**16**	**24**
Ca	g · 100 g^{-1} DM	S	12.6	10.3	19.7	2.7	1.9	7.0
		F	16.8	14.2	23.9	3.0	2.5	7.5
		%Δ	**33**	**38**	**21**	**11**	**30**	**7**
Ca	g/flask	S	60.1	48.4	111.1	11.8	7.9	32.3
		F	65.7	52.8	117.6	11.0	8.4	30.0
		%Δ	**9**	**9**	**6**	**−7**	**7**	**−8**
Mg	g · 100 g^{-1} DM	S	1.19	1.39	0.92	0.78	0.82	0.70
		F	1.61	1.78	1.07	1.04	1.12	0.93
		%Δ	**35**	**28**	**17**	**33**	**36**	**33**
Mg	g/flask	S	5.7	6.5	5.2	3.4	3.4	3.2
		F	6.3	6.6	5.3	3.8	3.8	3.7
		%Δ	**11**	**2**	**2**	**12**	**12**	**15**
Na	g · 100 g^{-1} DM	S	1.10	1.24	1.13	3.12	3.20	2.89
		F	1.42	1.68	1.25	3.93	4.22	3.85
		%Δ	**30**	**36**	**11**	**26**	**32**	**33**
Na	g/flask	S	5.2	5.8	6.4	13.6	13.1	13.3
		F	5.6	6.2	6.2	14.4	14.2	15.3
		%Δ	**6**	**8**	**−4**	**6**	**8**	**15**

AF = algae fiber; GS = ground seaweed; FB = fishbone; FM = fishmeal; and MU = mussels.

Na is not an essential nutrient for most plants, but it is important to assess, because many plants are sensitive to it at too high concentrations. The GS treatments had markedly higher Na concentrations and contents per flask than those with AF (Table 6). The highest Na concentration in a compost at completion was observed in GS + FM (4.22 g · 100 g^{-1}) and the lowest was observed in AF + MU (1.25 g · 100 g^{-1}).

3.4. Suitability as a Fertilizer

A well-balanced fertilizer should cover the demand for macronutrients in crop plants. For comparison, the average concentrations of nutrients found in plant shoot dry matter that are sufficient for growth [59] and the concentrations of nutrients in one of the most sold organic fertilizers on the market in Norway (Grønn 8, Grønn gjødsel AS, Rakkestad, Norway) are presented along with the composts in Figure 4. These references were applied to show the relative composition of nutrients in a well-balanced fertilizer compared with crop demand, shown as a column diagram with the relative values of DM concentrations on the y-axis. As can be seen, the commercial fertilizer has more P and Ca and less K and Mg than the concentrations found in plant tissues. This is explained by the fact that some P is absorbed in the soil, and not all P applied in a fertilizer is readily available for plant uptake, whereas K and Mg are often mineralized from soil minerals in addition to what is applied in fertilizer.



	Marschner	Grønn 8	AF+FB	AF+FM	AF+MU	GS+FB	GS+FM	GS+MU
Na			1.4	1.7	1.3	3.9	4.2	3.9
Mg	0.2	0.3	1.6	1.8	1.1	1.0	1.1	0.9
Ca	0.5	7.6	16.8	14.2	23.9	3.0	2.5	7.5
S	0.1	0.4	0.9	1.1	0.7	3.6	3.8	3.4
K	1.0	2	5.4	6.2	3.7	2.3	2.4	2.2
P	0.2	4	3.1	1.2	0.3	0.7	0.3	0.1
N	1.5	7.5	1.3	1.4	0.8	1.2	1.1	1.0

Figure 4. Concentrations and relative amounts of macronutrients in the finished composts compared with concentrations identified by Marschner (2012) [59] as sufficient for adequate plant growth and with Grønn 8, a commercially available poultry manure-based organic fertilizer sold in Norway.

For the composts, the DM concentration of N did not vary considerably and fell between 0.8 and 1.4 g · 100 g^{-1} in all of the treatments (Table 5, Figure 4). This is close to the 1.5 g · 100 g^{-1} identified by Marschner as the sufficient concentration in plant matter [59], but far too low for use as a commercial fertilizer. The selected fertilizer (Grønn 8) had 7.5 g total N per 100 g DM. The DM concentration of P was highly variable, ranging from 0.1 g · 100 g^{-1} for GS + MU to 3.1 g · 100 g^{-1} for the final compost of AF + FB. Again, the commercial fertilizer contained much more P than any compost, except for AF + FB. The DM concentration of K was about 2 g · 100 g^{-1} in the GS treatments (similar to Grønn 8), but well above this level in the AF treatments (4–6 g · 100 g^{-1}). All composts, and especially those made from GS, are good sources of K. As shown in Figure 4, the K concentration in Grønn 8 is low compared with crop demand.

The DM concentration of S was about 1 g · 100 g^{-1} in the AF and 3–4 g · 100 g^{-1} in the GS treatments, all of which are higher than Grønn 8. All composts, especially those made with GS, are good sources of S. The DM concentration of Ca was much higher in the AF treatments than in the GS treatments and highest when MU was applied as the N source, resulting in concentrations ranging from 2.5–7.5 g · 100 g^{-1} DM for GS to 14.2–23.9 g · 100 g^{-1} DM for AF. This is well above the concentration in the Grønn 8 fertilizer, which was relatively high compared with crop demand. The range of concentrations for Mg was relatively narrow between treatments, from 0.9 to 1.8 g · 100 g^{-1} DM. This is above the concentration in Grønn 8, which is low compared with crop demand. All composts, especially those made from AF, are good sources of Mg.

4. Discussion

4.1. Composting Process

The results confirm that it is possible to make compost based exclusively on marine residues, which are currently being wasted. All mixtures generated heat and showed reductions in volume and organic matter content (LOI), a decreased C/N ratio, and an increase

in pH. This is in line with results from the literature and other studies on composting presented in this article [18,22,29–31,34–36,38,45]. However, there were clear differences, especially when comparing the treatments by carbon source. It is difficult to determine whether it was the carbon source alone or if the differences in heat generation, volume reduction, and the degradation of organic matter resulted from variations in MC, BD, and C/N, or possibly pH and EC. None of these variables were the same for all treatments at the start of the experiment, though differences could be roughly grouped by the carbon-rich feedstock used. The mean MC for the AF treatments at the start was 64.0% (SD = 0.006), and 65.1% (SD = 0.005) for the GS treatments. While this is slightly above the optimum 50–60% value, the difference is rather small, and all MCs were within an acceptable range. For BD, the GS treatments were closer to optimal, i.e., less dense. Again, there was overlap, and the differences were not great. A higher BD can mean that there is less pore space for oxygen to fill, which, in turn, can lead to anaerobic conditions and cooler temperatures. However, in this experiment, the treatments with the higher BD (i.e., AF treatments) also had the highest temperatures.

Cole et al. made compost from a species of green seaweed (*Ulva ohnoi*) and sugarcane bagasse [29]. They tested a range of C/N ratios at the start of composting, from 11:1 to 50:1. The lowest C/N ratio became putrid and was terminated. All the others generated heat and followed similar temperature curves, confirming that the C/N ratio is a flexible parameter. What separated the treatments most was the final concentration of total N, which was highest in the 18:1 and 22:1 ratios. All treatments in our trial had C/N ratios within the optimal range of 25–35 at the start [38], with the AF treatments being on the lower end. GS + FM had the lowest C/N ratio among the GS treatments. However, GS + MU, which had the highest C/N ratio within this group (34), also had the highest mean temperature. For comparison, AF + MU had the highest C/N ratio among the AF treatments and the lowest mean temperature.

There was a clear difference in the pH between the AF and GS treatments (mean = 9.5 vs. 6.7). The pH of the GS treatments was much closer to optimal, whereas that of the AF treatments was well above that. This high pH, however, did not appear to hamper heat generation. An increase in pH during composting has been found in many studies, (e.g., [35,60]) and is explained by the emission of CO_2 and the formation of NH_3 [38,61,62]. Our study demonstrated that such an increase may occur even with highly alkaline feedstocks, and that a pH close to 10 did not hamper heat development or volume reduction. The higher pH also did not appear to contribute to higher losses of N in the form of NH_3 [63,64].

For EC, a clear difference between treatments was found regarding changes in EC during composting. The three treatments with AF exhibited an increase, whereas the three with GS ended lower than at the start of the trial (Figure 2). Most examples from the literature cite an initial increase followed by a decrease in the EC during composting [65–70], similar to what occurred for the GS treatments. In the current study, there was also an initial increase followed by a decrease in all treatments, though the degree of increase and subsequent decrease varied. In all treatments, the EC leveled off or increased again towards the end of the experiment. The initial increase was greatest for AF + FM and AF + FB, whereas the decrease was greatest for the GS treatments. These two AF treatments were also the warmest during the first phase. The initial increase in EC is likely due to the mineralization of N and the subsequent release of inorganic phosphorus and nitrogen ions [70,71]. The following decrease may then be caused by the volatilization of organic nitrogen and sulfur compounds, the precipitation of mineral salts, the microbial consumption of salts, and the degradation of soluble organic matter [69,70]. When composting is performed, outside leaching also contributes to a decrease in EC [69]. In our case, leaching did not occur, but soluble organic matter was degraded and precipitation and microbial consumption may also have occurred. The final levels of EC were quite high, and higher than most other composts in the literature (Table 7).

In general, the treatments with AF reached higher temperatures and maintained them longer than those with GS. The two treatments with MU saw the smallest reductions in volume, which could have been due to the high mineral content of the mussel shells. One possible explanation for the more efficient composting (more heat and greater volume reduction) with AF might be that the particle size was significantly smaller, hence making the degradation of carbon easier for the microorganisms involved [72]. At the same time, if particles are too small, the compost can become compact and anaerobic conditions may be created [38]. Ideally, feedstocks with a diversity of sizes and shapes are used [73]. Another possibility is that the Dewar flasks were filled too soon after the feedstocks were mixed and moistened. The ground seaweed was possibly still swelling, creating a more compact environment inside the flasks. Rockweed contains a high amount of alginates (20–40% DM), which can absorb a large amount of water and are resistant to biological degradation [74]. Fucoidans are another type of compound present in rockweed. They exhibit antimicrobial properties and are being increasingly used in the pharmaceutical and nutraceutical sectors as alternative antibiotics and anti-inflammatories [75]. They are also considered to be recalcitrant and degrade slowly. The conventional extraction of fucoidans involves acids and bases, similar to the process used on the rockweed in this study [75]. It is possible that these antimicrobial and recalcitrant alginates and fucoidans were still present in the ground seaweed, but had been removed from the algae fiber. The more compact mixture and the presence of these compounds may partly explain why the GS treatments were slower to heat up and did not degrade as much. A well-aerated material not only contributes to the supply of oxygen for autotrophic bacteria, but also favors the evaporation of water, which is the medium in which the CO_2 is dissolved; when the water content is reduced, the desorption of CO_2 is accelerated [38].

According to Miloştean and Flori [53], a mixture is deemed suitable for composting if the temperature rises above 40 °C in the Dewar flask. Körner et al. [39] concluded that larger-scale experiments are unnecessary when the substrates being tested in small-scale respiration experiments exhibit degradation-limiting properties, i.e., when an experiment ends in negative results, such as not initiating heat development. Dewar flask trials and other small-scale experiments can only be considered as a rough guide, since composting at larger scales has different dynamics than in the laboratory [39,51]. All of our treatments reached at least the 40 °C threshold and, in some cases, much higher, as exhibited by the number of thermophilic degree days (TDDs) in all treatments, especially those with algae fiber. While some of the treatments were above 55 °C for periods, none met the hygienization requirements. While respiration was not measured directly, the high temperatures and reductions in total C and volume imply that these feedstocks can be composted on a large scale.

4.2. Potential Application of Compost

The concentration of N in the composts was far below what would be required if the compost was applied as a fertilizer, but resembled the N concentration in plant material identified by Marschner [59] (Figure 4). The concentrations of all other nutrients varied widely, but were mostly higher than those found in plant shoots, especially S in the GS treatments and Ca in the AF treatments. None of the composts were balanced when the concentrations were converted to ratios. All had significantly less N than the commercial fertilizer Grønn 8 relative to the other nutrients, and all but AF + FB had lower concentrations of P. The composts were found to be good sources of S, K, Ca, and Mg. Composts are rarely applicable as the primary fertilizer source for crop plants and are often complemented by N fertilizers. This is due to N being lost during composting, though it is possible to minimize this loss [29]. However, they have a high content of organic matter (20–35% total C), which can be beneficial, because N-rich organic fertilizers such as feather meal contain little C. If composts can be enriched by N-rich marine material after maturation without re-starting a degradation process, the mixing of fish material

into composted seaweed could be one option for designing a complete and well-balanced marine-based fertilizer.

Other examples of seaweed-based composts and composts comprising non-marine feedstocks from the literature have shown varying nutrient profiles, and some variables overlap with the values in the current study (Table 7). The total N concentrations were similar to those in the non-marine composts and those reported by Cole [29]. The C/N ratios in this study were within the range of other composts, including non-marine composts. The pH for the AF composts was considerably higher than the other examples, but for GS, it was similar to the literature. The EC was considerably higher, even for composts made with marine feedstocks that contained high concentrations of Na. The only compost that was similar was that from Cole [29], which had an EC of 10.17 dS · m^{-1}. However, with the exception of the compost made by Szmidt [45], the other seaweed-based composts were above the limit of 1.0 dS · m^{-1} set by the EU Ecolabel scheme [76] and at the higher end or above the range typical for non-marine composts [77].

Table 7. Comparison of characteristics and nutrient concentrations of two composts from the current study and other seaweed-based composts from the literature. Ranges of characteristics from non-seaweed composts are included as a reference. C/N, pH, and EC values for AF + FM and GS + FB are taken from Table 4; nutrient values are taken from Tables 5 and 6.

		AF + FM	**GS + FB**	**Szmidt [45]**	**Cole [29]**	**Illera-Vives [35]**	**Stehouwer et al. [77] [2]**
	Feedstocks	Algae fiber from *A. nodosum* + fishbone	Ground and dried *A. nodosum* + fishbone	*A. nodosum* decanter waste + wheat straw + NH_4NO_3 + urea	Fresh sea lettuce (*U. ohnoi*) + sugarcane bagasse (start C/N 26)	Drift seaweed (*Laminaria* &, *Cystoseira* spp.) + horse mackerel (*T. trachurus*) + pine bark	Leaf and yard trimmings, food waste, manure, biosolids, urban waste
Characteristic	**Unit**						
C/N		17	24	35	20	22	12–23
pH		10.10	6.98	8.7	6.06	6.68	7.0–8.1
EC	dS · m^{-1}	17.43	9.23	1.07 [1]	10.17	2.47	0.96–3.96
tot-N	g · 100 g^{-1} DM	1.35	1.20	2.76	1.3	2.11	1.2–2.1
P	g · 100 g^{-1} DM	1.17	0.69	0.38	0.11	0.61	0.23–0.94
K	g · 100 g^{-1} DM	6.15	2.31	3.92	1.62	0.7	0.45–1.18
S	g · 100 g^{-1} DM	1.08	3.57	*	2.36	*	0.18–0.23
Ca	g · 100 g^{-1} DM	14.2	3.0	*	0.42	0.99	1.93–3.93
Mg	g · 100 g^{-1} DM	1.78	1.04	*	2.27	0.28	0.27–0.71
Na	g · 100 g^{-1} DM	1.68	3.93	*	2.76	1.02	0.05–0.20

* Not measured. [1] Converted from an extract ratio of 1:6 (v/v) compost:water to 1:5 as was used in the current study. [2] These values are a range of means presented in Tables 15.1–15.4 in Stehouwer et al. [77].

The high content of sodium in the final compost, especially in the GS treatments (about 4 g · 100 g^{-1} of DM), can be problematic for plant growth [69] and for soil aggregate stability when applied to finer-textured soil [78]. Illera-Vives [35] made compost with fish waste and seaweed with a concentration of Na of 1 g · 100 g^{-1} in the final product. She deemed this too high for arid and semi-arid regions, but not for humid areas, where precipitation quickly washes the Na out of the root zone. The compost from Cole [29] had an even higher concentration of (2.76 g · 100 g^{-1}). All the marine composts in Table 7 for which the Na was measured have concentrations well above the non-marine composts. One indicator of potential sodium toxicity is the K:Na ratio. The exact ratio depends on the plant, climate, and soil type, but it is recommended that it should be at least 2:1 or more in the growth medium [69,79]. Higher concentrations of Na can disrupt potassium homeostasis in cells and whole plants and suppress the influx of K [80]. Plants may tolerate sodium and chloride, but use significant energy to cope with high concentrations, and when toxic concentrations are reached, they will rapidly die [81]. In our experiment, the K:Na ratio was about 0.6 for the GS treatments, failing to meet the recommendation. In the AF treatments, the ratio was between three and four, probably due to the industrial treatment with KOH. At the same time, the relatively high Ca concentrations, especially in the GS + MU treatment, could help to ameliorate some of the toxic effects of the high Na^+ concentration when applied to soil [69,79].

EC measures the cumulative soluble salt content, including the ionic elements in soil, compost, and solutions [69]. Soils with an EC_e (determined with a saturated paste extract) of >4 dS · m^{-1} are often considered to be saline, depending on the pH and ratios of ions [69]. However, the literature suggests that composts with an EC_5 (determined using a compost/deionized water ratio of 1:5, as was performed in the current study) of ≥5 dS · m^{-1} can still be beneficial for soils due to the high content of organic matter. One study found that mixing seaweed-based compost with an EC of 15 dS · m^{-1} into soil improved the yields of tomatoes, known to be a salt-sensitive crop, compared with the control [67]. This was possibly due to beneficial compounds in seaweed that increased resistance to osmotic stress. Adding compost to soils, even saline soils, can improve conditions by decreasing the proportion of exchangeable sodium, increasing the cation exchange capacity (CEC), and improving infiltration and the water-holding capacity [67,69,82]. However, reducing the NaCl content, if possible, is recommended, especially when applied often. Hence, composts may be more applicable as ingredients in a complete fertilizer than as a soil amendment, but further studies of a larger scale are required to reach conclusions about this.

Another issue with soil amendments made from marine materials is that their concentrations of potentially toxic elements may be significant. Seaweeds may contain high concentrations of arsenic and cadmium; hence, their application as soil amendments may be regulated by such concentrations, rather than the content of nutrients. With current Norwegian regulations, which do not comprise any regulations for arsenic, the concentration of cadmium (Cd) restricts the application of seaweed materials from brown macroalgae. Algae fiber commonly contains 1–2 mg of Cd per kg DM [83]; the batch applied in the current study had 2.0 mg (analyzed at Nemko Norlab, Namsos, Norway), bringing it to the limit of what can be applied as an amendment to agricultural soil, according to Norwegian regulations [84]. The same batch contained 17 mg of arsenic (As) per kg DM. The ground seaweed contained 0.5 mg of Cd and >40 mg of As per kg DM. The fishbone contained 0.02 mg of Cd and 0.8 mg of As, the fishmeal contained 0.03 mg of Cd and 16 mg of As, and the mussels contained 0.01 mg of Cd and 1.4 mg of As per kg DM. Arsenic is easily methylated, hence, it occurs as organic As in living organisms. Organic As is not considered to be toxic, but inorganic As is highly toxic, and the EU regulation for organic fertilizers [85] has a limit of 40 mg of inorganic As per kg DM in soil amendments. The level of inorganic As in seaweed is probably well below this limit, but this needs further exploration.

5. Conclusions

Our experiments confirmed that it is possible to produce compost exclusively from marine-derived materials with expanded clay aggregates as a bulking agent. All treatments reached thermophilic temperatures (>45 °C) and saw reductions in volume, organic and dry matter content, C/N ratio, and moisture content, demonstrating successful degradation due to the thermophilic, microbial decomposition of organic matter. The combination of algae fiber and fishmeal performed best based on the temperature profile, volume reduction, and other parameters. All the composts were rich in sulfur, calcium, and, in some cases, magnesium and phosphorus. However, none of them contained enough nitrogen to perform as a complete fertilizer alone, they all had a high electrical conductivity (9–17 dS · m^{-1}), and those made with ground seaweed contained far too much sodium. In arid climates, these composts could be added in the autumn, when there is more precipitation or land is fallow, to reduce the risk of sodium toxicity. Another solution could be to rinse the feedstocks with fresh water before composting or allow the compost to mature outside. The application of this compost to agricultural soil in humid climates should not be problematic, and could contribute valuable nutrients and organic matter to the soil. On the other hand, the high organic matter content and concentrations of K+ and Ca+ ions might counteract the negative effect of Na, especially in composts made with algae fiber and mussels. Due to the lack of nitrogen, all these composts would benefit from being combined with a nitrogen-rich material. Composting marine residues such as

those presented here could facilitate their integration into existing value chains for organic fertilizers and contribute to decreasing the dependency on conventional fertilizers while adding valuable nutrients and organic matter to agricultural soils.

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