
Baltic
MUPPETS

D3.3 Evaluation Report on Plant Experiment Results

Havsmineral Fertilizer & Compost Products

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CONTENT

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1. INTRODUCTION

Mussel farming in the Baltic Sea offers a dual benefit of environmental restoration and resource optimization. By reducing eutrophication, it positively impacts the fragile marine ecosystem while creating opportunities to repurpose mussel byproducts into valuable agricultural inputs. To ensure the economic sustainability of mussel farming, it is essential to develop innovative uses for both mussel shells and meat. Addressing this challenge, Grobruket has developed complete mineral fertilizers under the title of “Havsmineral”, utilizing ground mussel shells as a substitute for conventional lime products. An additional compost product, Havskompost, utilizing waste materials from the fish and mussel industries has also been tested.

Due to low salinity, Baltic Sea mussels are often smaller and, therefore, not always suitable for the human consumption market. In the western Baltic Sea, small mussels are considered a side-stream of market-size mussel production. Baltic MUPPETS is a three-year project funded under the Interregional Innovation Investment (I3) Instrument and aims to create a new value chain for small mussels in the Baltic Sea Region (BSR) by developing high-value and healthy pet food products. The motivation behind this initiative lies in the prospect of simultaneously restoring the Baltic Sea ecosystem and harnessing byproducts to tackle pressing ecological and economic challenges. This unique convergence of environmental restoration and resource optimization highlights the transformative potential of sustainable innovation.

As part of the Baltic MUPPETS project, Grobruket has embraced the challenge of creating sustainable soil amendments and fertilizers from waste mussels and other ocean-based resources. This approach not only addresses waste management but also enriches soil health and aligns with circular economy principles. By reducing reliance on synthetic fertilizers and repurposing abundant, nutrient-rich marine resources, Grobruket is advancing agricultural sustainability.

Grobruket, a knowledge-driven company, specializes in pioneering sustainable methods for plant cultivation, focusing on plant nutrients, bio-stimulants, and substrates. Through cutting-edge research and innovation, Grobruket strives to optimize crop health and productivity while promoting environmental stewardship. Their work in this project exemplifies their commitment to creating a more resilient and sustainable future for horticulture.

This report evaluates the outcomes of plant experiments conducted with fertilizers and compost products derived from mussel farming byproducts, assessing their potential to enhance soil and crop productivity in an environmentally sustainable manner.

1.1 Background

The aim of Grobruket's work in the Baltic MUPPETS project has been to create a new value chain for the use of waste mussels and mussel shells from processing industry mussels from the Baltic Sea for agricultural purposes. The goal is to introduce a range of fertilizer products that support both marine and terrestrial ecosystems, creating a closed-loop system between production and consumption.

Grobruket has focused on two types of agricultural products that effectively reduce marine waste. The first product, **Havsmineral, is a slow-release fertilizer based primarily on organic and circular ingredients** with key nutrients sourced from the sea. The second product, **Havskompost, is a compost product composed of fish and mussel waste materials that have undergone a thermal composting process**.

To develop the products, a thorough nutrient analysis has been conducted of possible input materials such as mussel shells, mussel meat as well as other locally produced and organic nutrient sources such as kelp and biochar produced in Sweden. Fertilizer and compost recipes are created to fit a specific fertilizer profile whilst providing optimal nutritional values that fulfill the requirements of many types of plants. A key component in the development of the products are the cultivation experiments. These experiments test the recipes, dosage and application methods to ensure that the product delivers ideal results for most growers. This report will provide a summary of the results of the cultivation experiments.

1.2 A complete fertilizer

A complete fertilizer provides plants with all essential macronutrients and micronutrients required for healthy growth and development (Marschner, 2012). These nutrients include nitrogen (N), phosphorus (P), and potassium (K), commonly referred to as NPK, along with secondary nutrients such as calcium (Ca), magnesium (Mg), and sulfur (S) (ibid). Additionally, micronutrients like iron (Fe), manganese (Mn), boron (B), zinc (Zn), copper (Cu), molybdenum (Mo), and chlorine (Cl) play vital roles in plant metabolism, enzyme activation, and stress tolerance (ibid).

To be classified as a complete fertilizer, a nutrient formulation must contain all essential elements in balanced proportions suited to the specific needs of the plant species and growth conditions (Havlin et al., 2014). Synthetic fertilizers, organic amendments, and bio-based solutions such as compost extracts or hydrolyzed proteins can serve as complete fertilizers, depending on their composition and nutrient availability (ibid).

An optimal complete fertilizer must also account for nutrient interactions, avoiding imbalances that could lead to deficiencies or toxicities (Hawkesford, Barraclough, and De Kok, 2012). For example, excessive nitrogen application can reduce phosphorus uptake, while high calcium levels may interfere with magnesium and potassium absorption (ibid). Therefore, precise formulation and application rates are crucial to ensuring that plants receive adequate nutrition without causing environmental harm through nutrient leaching or accumulation (Fageria, Baligar, and Jones, 2011).

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1.3 Compost

The process of composting is an effective method for managing solid waste, as it transforms organic material into stable organic matter rich in essential plant nutrients (Mahapatra, Ali and Samal, 2022). Composting is an ideal and sustainable method of waste management within the circular economy (ibid).

Compost can only be applied if it has fully matured and does not contain any substances that could be harmful to plants (Mahapatra, Ali and Samal, 2022). Ensuring that the compost is well-decomposed and free from phytotoxic compounds is crucial, as its effect on seed germination and plant growth determines its suitability for use (ibid).

Similar to a complete fertilizer, one of the most important qualities of a compost is the amount of plant-available nutrients that it contains (Sullivan and Miller, 2001). The level of plant-available nitrogen is of especial importance for plants (ibid). However, achieving the correct balance in the concentration of nutrients and soluble salts is crucial (ibid). A compost containing too high salt content can negatively affect seed germination and root development (Sullivan and Miller, 2001).

1.3.1 Compost process

The composting process involves several key stages to transform organic waste into nutrient-rich compost (Mahapatra, Ali and Samal, 2022). Initially, organic materials are combined with dry bulking agents like cow dung, shredded paper, or rice hulls to create a structure that facilitates microbial activity (ibid). In the first phase, mesophilic microorganisms (those that thrive at moderate temperatures) begin decomposing the organic matter, breaking it down into smaller particles (ibid). This breakdown increases the surface area, accelerating the decomposition process (ibid). Regular mixing is essential during this stage to maintain adequate aeration; insufficient oxygen can hinder moisture evaporation and slow decomposition (ibid). The microorganisms also help maintain a porous structure in the compost, aiding in the distribution of water and nutrients (ibid).

Maturity refers to the degree to which the composting process has been completed (Mahapatra, Ali and Samal, 2022). The more mature the compost, the more thoroughly the organic material has decomposed, bringing it closer to becoming a stable and nutrient-rich soil amendment (ibid). It is a measure of how far the compost has transformed from its original ingredients into a beneficial product for plant growth (ibid).

Stability, on the other hand, refers to a specific state of the organic material or a particular phase in the decomposition of compost (ibid). The purpose of stabilization is to ensure the final product remains stable, preventing decomposition, excessive heating, oxygen depletion, foul odors, or pest attraction (Sundberg, 2005). The resulting compost is beneficial as it enriches the soil with nutrients, improves soil structure, and can aid in suppressing plant diseases (ibid). Stability relates to how well the compost maintains its properties over time and under different conditions (Mahapatra, Ali and Samal, 2022). A stable compost is less likely to undergo further decomposition or emit unpleasant odors, and it provides more consistent and long-term nutrient availability for plants (ibid).

While maturity assesses how complete the composting process is, stability focuses on the quality and durability of the resulting compost as a useful product (ibid). Understanding both maturity and stability is essential for evaluating compost quality and its suitability as a soil amendment (ibid).

An immature compost generates odor and has a high risk of toxicity (Sullivan and Miller, 2001). A mature compost should have a pH level of between 6-6,5. Organic acids reduce microbial activity and suppress organic waste degradation due to which the composting and the subsequent maturation are slow up to inefficient at the low pH (Sundberg, 2005).

During the composting of food waste, an extended initial acidic phase can sometimes occur, leading to a slower breakdown of materials (Sundberg, 2005). In effective composting, this early phase transitions into a high-efficiency stage, characterized by pH levels above neutral (ibid). However, if temperatures rise above 40°C while the pH remains below 6, the composting process can be significantly hindered (ibid).

The most common measure of compost stability are self heating tests where the maximum rise in temperature of moist compost is measured over a 5-10 day period (Brinton, 2000). Excessive heating (>20°C increase in 10 days) indicates unstable compost (ibid). Furthermore, it is common to test the maturity and stability of a compost using germination tests (Mahapatra, Ali and Samal, 2022).

1.3.2 Composting methods

Compost can be created using multiple methods. The most common methods are described below (Brinton, 2000).

Turned Windrows: This is the most common method for rapid composting of yard wastes (ibid). A windrow is an elongated pile that is turned periodically to maintain aerobic conditions, thereby accelerating the composting process (ibid).

Aerated Static Piles: This method involves forming piles of organic waste and using a forced aeration system to supply oxygen, eliminating the need for turning (ibid). It's suitable for large volumes of homogeneous waste (ibid)

Static Pile with Passive Aeration: This method involves composting smaller volumes of materials using passive aeration to maintain optimal temperature and oxygen levels (United States Environmental Protection Agency). Adding bulking agents such as wood chips and sawdust is important to reduce density and increase air flow (ibid).

In-Vessel Composting: In this technique, organic waste is composted within a controlled environment, such as a drum, silo, or concrete-lined trench (Brinton, 2000). This allows for precise control of environmental conditions, leading to faster decomposition (ibid). This can include using compost machines (United States Environmental Protection Agency).

Vermicomposting: This method utilizes specific worm species to decompose organic waste, resulting in high-quality compost known as vermicompost (Brinton, 2000). It's particularly effective for processing food scraps and other organic materials (ibid).

1.4 Nutritional value of mussel products

Mussels can serve as a fertilizer in organic farming, where nutrient input is necessary, but access to suitable fertilization options is restricted (Spånberg, Jönsson & Tidåker, 2013). As filter feeders, mussels absorb nutrients from their surroundings, primarily from phytoplankton (ibid). By harvesting and applying them to agricultural land, these retained nutrients can be transferred from the marine environment to the soil, helping to reduce eutrophication (ibid).

Olrog and Christensson performed multiple field trials using whole mussels, mussel remains and mussel-based compost (2008). The trials showed that using mussel material can increase harvest significantly (ibid). The fertilizer value per ten tonnes when using a dosage equal to 120 kilo nitrogen per hectare for whole mussels was calculated to 2280 SEK per ten tonnes, fresh mussel remains was calculated to 2660 SEK per ten tonnes and composted mussel remains to 710 SEK per ton (ibid).

It is important to note that raw mussels are classified as animal by-products and must therefore be hygienically treated either by boiling or heat treatment prior to composting or further processing in fertilizer products (Minnhagen, 2024). Composting of raw mussels must take place in a closed container (in-vessel composting) with a heat treatment occurring during the composting process (ibid). All mussel products used by Grobruket have been boiled prior to use.

1.4.1 Mussel shells

The shell of the blue mussel (*Mytilus trossulus x edulis*) is composed of over 90% calcium carbonate, which shares the same chemical composition as pulverized limestone, the most commonly used lime product (Persson, 2024). The calcium carbonate in mussel shells is much more soluble, which means it can effectively increase soil pH even without being finely ground (Olrog & Christensson, 2003). The shells can therefore be used as a buffer to raise soil pH and counter acidity (ibid). When added to acidic soils, the calcium carbonate in the shells neutralizes the excess hydrogen ions in the soil, reducing acidity and increasing the pH (ibid). Additionally, the shells contain phosphates and sulfates, which can provide a nutrient boost for plants in the soil (ibid). This makes mussel shells an effective and sustainable alternative to traditional lime for soil amendment (ibid).

Grobruket AB assisted Norea Persson in her bachelor thesis work in which she compared the use of mussel shell meal to limestone flour (2024). Persson's experiment studied the effect on pH of coarsely ground mussel shells (0,63-2mm) and finely ground mussel shells (>0,25) (ibid). The results showed that both treatments had a pH–raising effect (ibid). The experiment showed that ground mussel shells could replace limestone flour as a liming product to be used in pots of soil (ibid).

Grobruket sent washed mussel shells for laboratory analysis that provided the nutritional content of the shells. The results (Table 1) showed that in addition to providing a high calcium content, mussel shells can also be a source of magnesium and provide smaller amounts of phosphorus, potassium, and iron (LMI AB, 2024). However, mussel shells also contain a high level of sodium and sulfur (ibid).

Table 1: Grobruket sent finely ground washed mussel shells for total laboratory analysis (LMI 2024). The total analysis provides the total amount of nutrients in the shells (ibid).

SUBSTANCE	TOTAL ANALYSIS (MG/KG)	SUBSTANCE	TOTAL ANALYSIS (MG/KG)
CaO	42 % of weight (Not mg/kg)	Mn	94
Al	130	Mo	1.21
B	11	Na	2000
Ca	301000	Ni	9.14
Cd	0.22	P	1100
Cu	7.4	S	2300
Fe	220	Si	160
K	540	Zn	150
Mg	1070	Tot-N	20100

1.4.2 Mussel meat

The meat content in small mussels is mainly used for animal feed, but meat waste, or badly separated meat with too much shell residue can also be used as a fertilizer (Spångberg, Jönsson & Tidåker, 2013). It makes a nutrient rich input for fertilizer and can be a source of nitrogen, calcium, phosphorus and micro-nutrients such as iron (Table 2) (Eurofins Agro, 2024; Spånberg, Jönsson & Tidåker, 2013).

Table 2: Nutritional content of a pooled sample of three different batches of separated and dried mussel meat analyzed by Eurofins Agro (2024).

ANALYSIS	PARAMETER	VALUE (g/100g)
Crude Protein (Nx6.25) (Dumas)	Crude Protein (Nx6.25)	56,2
Crude Fat	Crude Fat	10,7
Fiber (FiberCap)	Fiber	1,1
Moisture Content	Moisture	2,86
Ash	Ash	24,5
NFE	NFE	4,6

ANALYSIS	PARAMETER	VALUE (mg/kg)
Magnesium	Mg	980
Phosphorus	P	9300
Potassium	K	300
Calcium	Ca	100000
Manganese	Mn	70
Iron	Fe	430
Copper	Cu	9,8
Zinc	Zn	85
Sodium	Na	4200

1.4.3 Struvite

Struvite is a circular source of phosphorus, magnesium, ammonium and other minerals recovered from wastewater treatment plants (Achilleos, Roberts & Williams, 2022). Phosphorus precipitation causes problems within wastewater treatment facilities due to mineral build-up creating blockages in return lines, pumps and valves (ibid). Struvite crystals can be extracted using a crystallisation reactor (ibid). Phosphorus produced from phosphate rock is commonly used for synthetic fertilizers but phosphate is a finite source and its mining can be problematic (Geissler et. al., 2018). By extracting struvite and using it as an input for fertilizers it solves the problem of problematic build-up in the waste water treatment plants whilst not depleting the earth's source of phosphate (ibid). Struvite is an effective

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input in slow-release fertilizers as it contains 12,5% phosphorus, 5,7% nitrogen and 9,9% magnesium (Ekobalans, 2020). The companies Ekobalans and Ostara produce struvite crystal extraction technology and are active in struvite production in Europe (Ekobalans, 2020; Ostara, 2025). Struvite recovery is expected to reduce 1,6% of phosphate rock mining whilst also reducing waste, effectively closing the phosphorus loop in soil-crop-animal-human soil cycle (Shu et al., 2006).

1.4.4 Nutritional content of additional plausible organic inputs

Additional nutrient inputs besides mussels are required for Havsmineral to attain a complete nutritional profile. Ideally, these inputs stem primarily from circular organic ingredients as opposed to mineral inputs. Table 3 shows two plausible inputs that are of circular or sea origin.

Wild rockweed, *Ascophylum nodosum* can provide a fertilizer with a natural source of many micronutrients as well as vital macronutrients such as potassium and magnesium (Sneckenström, 2025). Sugar kelp has a similar profile to rockweed but contains more potassium, phosphorus and nitrogen (LMI AB, 2024). Sugar kelp can contain two to four times more phosphorus than rockweed (Ometto et. al 2018). The sugar kelp used by Grobruket is organically grown in Sweden (Nordic Seafarm, 2025). However, the risk to using seaweed products such as sugar kelp and rockweed as fertilizer inputs is that these products contain a high concentration of sodium and sulphur (LMI AB, 2024). Too high concentrations of sodium can hinder uptake of water and other nutrients as a result of salt stress (Machado & Serralheiro, 2017). Therefore, in addition to careful analysis of the complete fertilizer composition as well as dosage testing has been performed in the plant cultivation trials.

Table 3: Nutritional content of rockweed, and biochar. The values are provided in mg/kg from a dry total nutrient analysis of the products conducted by LMI AB, Sweden.

SUBJECT	ROCKWEED	BIOCHAR
Al	6,2	3,1
B	53	1,9
Ca	1800	2600
Cu	0,31	<0,16
Fe	32	9,5
K	7900	7900
Mg	1900	690
Mn	3,7	22
Mo	0,31	0,32
NH4-N	8,3	56
NO3-N	28	12
Na	23000	170
P	440	1900
S	5700	120
Zn	14	6
pH	6	10

Biochar can also be used as a sustainable source of potassium, calcium and phosphorus (LMI AB, 2024). It is produced by the pyrolysis of biomass which creates a carbon-rich and solid residue (Lehman, 2007). Biochar is an interesting product to test as it has the ability to charge itself with ammonium, phosphorus and other nutrients due to its highly porous microstructure and vast surface area (Lehman 2007; Zhou et. al., 2021). This can help release nitrogen slowly and reduce leakage of nitrogen to leachate (ibid). However, the release pattern of biochar can be unpredictable meaning that using this as an input also requires thorough testing (Lehman, 2007). Biochar can be added to both compost and fertilizer products (Kamman, 2015).

1.4.4 Mineral inputs to Havsmineral

In addition to organic components, Havsmineral fertilizers also include 30-40% mineral components depending on the recipe version. These mineral components include ammonium sulphate, potassium sulphate, and micronutrients. Circular sources of ammonium sulphate can be used which is a waste product of steel manufacturing (Biototal Group). Circular sources of potassium sulphate include utilizing a waste stream from battery production (Cinis fertilizer). Future recipe testing strives to further eliminate mineral inputs such as micronutrients by replacing them with seaweed sources.

1.4.5 Additional inputs to Havskompost

Additives to compost are important for the compost structure as well as for the composting process (Mahapatra, Ali and Samal, 2022). Organic materials are combined with dry bulking agents to facilitate microbial activity (ibid). Additives such as sawdust or other bedding materials are used to provide structural support, regulate moisture content and increase the porosity of the material (Shahzad, 2017). These additives help maintain optimum free air space during composting (ibid). Sand can be added to help reduce nitrogen loss (Cheng et. al., 2022).

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2. CULTIVATION EXPERIMENTS

The cultivation experiments for Havsmineral fertilizers study how the fertilizer impacts the plants in terms of appearance and biomass. The studies also look at soil nutrient levels to assess the availability of nutrients to the plants over time. After each of the experiments are finalized the data is analyzed and recommendations are made for adjustments to recipes and suggestions for future experiments.

The cultivation experiments for Havskompost, focus on seed germination and plant growth (biomass). Furthermore, the experiments assess the maturity and stability of the compost which is essential for evaluating compost quality and its suitability as a soil amendment.

The cultivation experiments for both Havsmineral and Havskompost are conducted with a precise methodology and in controlled greenhouse conditions.

All data collected throughout the experiments is analyzed statistically to determine whether the results are significant.

2.1 Methodology - Havsmineral cultivation experiments

The effectiveness of fertilizer recipes is evaluated based on their impact on plant growth and appearance. The experiment begins with 1-liter pots filled with a nutrient-poor substrate mix, to which a measured dose of fertilizer is added. The fertilizer dosage is determined according to the nitrogen requirement of the selected plant species, ensuring comparability by normalizing dosages based on the nitrogen content of each fertilizer.

Before transplantation, seeds are germinated in coconut fiber and peat plugs until they reach the cotyledon stage. At this point, seedlings are transplanted into the prepared pots. Each treatment group typically consists of 5–10 replicates, with growth comparisons made against a control group (common store bought fertilizer and or Grobrukets mineral fertilizer, Biomineral) and, when applicable, a zero control (substrate only).

Experiments typically run for approximately four weeks. At the end of the experiment, visual assessments of plant health are conducted, and above-ground biomass is harvested and weighed. Additionally, soil nutrient analysis is performed at both the beginning and end of the study to assess nutrient retention and availability. Results are statistically analyzed to determine significant differences between treatments. This methodology ensures consistency and reliability across trials, allowing for accurate evaluation of fertilizer effects on plant growth.

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Image 1: Cultivation experiment testing the fertilizer product, Havsmineral, for growing basil. The experiment took place in the greenhouse at SLU during November and December 2024.

2.2 Methodology - Havskompost cultivation experiments

The Havskompost tested in the cultivation experiments was created using in-vessel composting. Some of the recipes endured an additional stage of composting in an outdoor static pile with passive aeration. Different inputs and composting methods and periods were tested for their maturity and stability states and to see the impact on seed germination and plant growth via biomass.

2.2.1 Seed germination tests

An open and a closed test were conducted to determine whether there was a difference in the germination rate of seeds across different substrates. Using an open and closed test shows whether a gas build up occurs within the container from the compost.

In the open test, the substrates were placed in round 9 cm pots, with 1 g of seeds spread on top. The pots were then watered and covered with plastic film. Moisture levels were maintained by watering as needed, and the plastic film was removed from all pots simultaneously after a certain level of germination was observed.

In the closed test, 500 ml of substrate was placed in 1000 ml airtight glass jars, with 1 g of seeds positioned along the inner edge of each jar. The jars were then watered and sealed.

Both tests were placed in a climate chamber with conditions set to 26 degrees, 45% relative humidity and 16 hours of light. After seven days, the seedlings had reached sufficient size for evaluation. In the open test, biomass was measured, while in the closed test, visible root growth was assessed.

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2.2.2 Growth performance

The growth performance test was a continuation of a closed test and followed the same methodology described in that section. The containers were opened after 26 days. Smell and visual observations and size of seedlings were noted.

2.2.3 Composting method

To evaluate the composting process, the method involves analyzing the initial material composition, including nutrient content and structural properties, to predict decomposition efficiency. Throughout composting, heat generation is monitored, along with periodic nutrient and moisture assessments. The final product is evaluated for nutrient levels, electrical conductivity, and salinity, with germination tests determining plant compatibility. Challenges such as nitrogen deficiency, odor management, and structural imbalances are addressed by adjusting inputs and composting conditions. The results guide final recommendations to ensure the compost is stable, nutrient-rich, and suitable for agricultural use.

3.1 Results of cultivation experiments for Havsmineral

Table 4: An overview of the cultivation experiments performed for the development of Havsmineral.

DATE	STUDY FOCUS AREA	RECIPE TESTED	PLANT SPECIES USED
2024-07-18	Recipe development - Growth performance evaluation	Havsmineral using arginine-phosphate and Havsmineral using potassium nitrate.	Komatsuna (*Brassica rapa* 'Malachai')
2024-09-19	Recipe development - Growth performance evaluation	Havsmineral V2 using arginine-phosphate and Havsmineral V2 using potassium nitrate.	Komatsuna (*Brassica rapa* 'Malachai')
2024-11-06	Recipe development - Growth performance evaluation	Havsmineral using rockweed as a natural source of potassium. The addition of biochar was also tested. (Havsmineral rockweed & biochar V1, Havsmineral rockweed without biochar V1).	Komatsuna (*Brassica rapa* 'Malachai')
2024-12-10	Recipe development - Growth performance evaluation	Havsmineral sugar kelp & biochar V2, Havsmineral mussel meat & biochar V2, Havsmineral blood meal & biochar V1.	Basil (*Ocimum basilikum L.* 'Genovese Sweet Aroma 2')
2025-01-07	Recipe development - Growth performance evaluation	Havsmineral sugar kelp & biochar V2, Havsmineral musselmeal & biochar V2, Havsmineral blood meal & biochar V1.	Basil (*Ocimum basilikum L.* 'Ordinary')
2025-02-03	Recipe development - Growth performance evaluation	Havsmineral sugar kelp V2 with and without biochar, Havsmineral mussel meat V3 with and without biochar, Havsmineral blood meal V2.	Basil (*Ocimum basilikum L.* 'Ordinary')

Havsmineral using arginine phosphate produced results equal to Grobrukets mineral fertilizer, Biomineral. Havsmineral using potassium nitrate did not produce results equal to Grobrukets mineral fertilizer. Both fertilizers resulted in on average higher plant biomass than plants grown without a fertilizer.

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Havsmineral V2 using arginine phosphate produced results equal to Biomineral. Havsmineral V2 using potassium produced slightly poorer results than Biomineral. However, the difference between Havsmineral and Biomineral was not statistically significant. Both fertilizers resulted in on average higher plant biomass than plants grown without a fertilizer. The arginine phosphate product was no longer available for purchase and further recipe development was required to replace this key input ingredient.

The Havsmineral recipe containing rockweed was tested with and without biochar. Both recipes provided the plants with sufficient levels of potassium. The recipe using biochar resulted on average in healthy plants with the highest biomass as compared with plants grown with Havsmineral with seaweed but without biochar as well as plants grown with Grobruket's mineral fertilizer. Biochar can be charged with ammonium and other nutrients which can potentially be used to release nutrients at a slower rate thus minimizing nutrient runoff in the leachate. Rockweed is naturally high in potassium but also contains high levels of sodium. A spurway analysis of the soil at the end of the experiment showed high levels of sulphates. Some plant species are sensitive to high levels of sodium and sulphate. Thus further testing was required to guarantee optimal results.

Additional recipes using organic Swedish sugar kelp and mussel meat were tested with the aim to use locally grown and organic ingredients from the sea to replace mineral inputs. The recipes were developed to contain lower levels of sodium and sulphate. The results indicated that the dosage needs to be adjusted. Analysis of the dried fertilizer using Havsmineral recipe with sugar kelp and biochar V1 as well as the electrical conductivity of the soil at the end of the trial showed that the dosage level needs to be adjusted. There was no statistical significance between the biomass of the plants grown with the Havsmineral fertilizers and plants grown with the control fertilizer, Chrysan. The plants all showed signs of intervenal chlorosis which can be a symptom of magnesium deficiency.

The plants grown with the Havsmineral fertilizers (Havsmineral sugar kelp & biochar V2, Havsmineral mussel meat & biochar V2, Havsmineral blood meal & biochar V1) showed strong chlorosis with necrotic spots on the older leaves. These symptoms indicate a severe nitrogen deficiency. There was no significant difference between the plants grown with the Havsmineral recipes, however, these plants had on average significantly lower biomass as compared to the plants grown with the control fertilizer. The recipe dosage was lowered by 23,5%. The amount of biochar used was increased from 1g to 2g and the application method was adjusted so that it was mixed directly into the fertilizer instead of being applied separately to the individual plant pots as done previously. Additionally, the level of potassium sulfate was reduced and the amount of struvite was also adjusted. A new recipe using blood meal, a waste product from the meat industry, is tested as an alternative to mussel meat and mineral inputs. The results clearly indicate that further adjustments need to be made to the dosage and recipes. The amount of biochar and the application method may have negatively impacted nutrient availability, as the biochar might have bound the nutrients, reducing their direct availability to the plants.

The most recent experiment tested the recipes Havsmineral sugar kelp V2 with and without biochar, Havsmineral mussel meat V3 with and without biochar, Havsmineral blood meal V2. The recipes had been adjusted by adding more calcium, magnesium and micronutrients. Havsmineral sugar kelp V2 and Havsmineral mussel meat V3 recipes were also tested with and without biochar and with two different dosage levels, 3g and 6 g. The plants grown with the lower dosage showed signs of chlorosis indicating a lack of nitrogen. There was no difference between the plants grown with and without biochar when receiving the same dosage amount. These plants all had clear signs of chlorosis and were shorter and less robust when compared to the control group and the group of plants that received the higher dosage. The plants that received the higher dosage showed minimal signs of chlorosis and were on average larger than the control group. Outgoing spurway analysis of the soil at the end of the experiment showed that regardless of dosage, all pots had very low levels of nitrogen left in the soil. The pots that received 3g av Havsmineral (both recipes) had low levels of calcium, potassium, manganese, and iron. However, these pots had excessive amounts of micronutrients, sulphur and sodium. The soil in the pots that received 6g of Havsmineral sugar kelp V2 had good levels of phosphorus, potassium and calcium. However, these pots had excessive amounts of magnesium, sulphur, sodium and micronutrients. The soil in the pots that received 6g of Havsmineral mussel meat V3 showed lower levels of potassium, calcium and manganese but excessive amounts of magnesium, micronutrients, sulfur and sodium.

3.2 Results of cultivations experiments for Havskompost

Table 5: An overview of the cultivation experiments performed for the development of Havskompost.

DATE	STUDY FOCUS AREA	RECIPE TESTED	PLANT SPECIES USED
2024-07-03	Seed germination	Mussel compost compared to a control consisting of generic planting soil mixed with 20% sand.	White mustard (*Sinapsis alba*)
2024-07-10	Seed germination	Closed test: Purchased green compost (control), Grobrukets garden compost turned once, Grobrukets garden compost turned twice.	Radish (*Raphanus sativus*)
2024-07-18	Seed germination	Open test: Sieved Grobruket garden compost turned twice, purchased green compost (control). Closed test: Sieved garden compost turned twice.	Cress (*Lepidium sativum*) (open), Radish (*Raphanus sativus*) (closed)
2024-08-13	Growth performance	Closed test: Purchased green compost (control), sieved Grobruket garden compost that was turned twice, mussel compost.	Cress (*Lepidium sativum*)
2024-08-15	Compost quality	Mussel compost V1 consisting of 75% washed mussel shells and 25% wood fiber, mussel compost V1 mixed with 2 parts fish waste and 1 part wood fiber added on 3 occasions during a 3 week period.	No plants used
2024-08-23	Seed germination	Open test: Turbofiber, Hortifiber, coconut fiber, mussel compost V5 (75% washed mussel shells and 25% hortifiber), seedling soil.	Cress (*Lepidium sativum*)
2024-09-24	Seed germination	100% fish compost, 66% mussels and 33% sea reed, 50% mussels, 25% grass cutting, 25% sea reed.	Pelargonium (*Pelargonium x hortonum* 'Apache appleblossom'), Komatsuna (*Brassica rapa* 'Malachai')

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3.2.1 Results of seed germination tests

The studies mainly evaluated the suitability of various composts and fiber-based substrates for plant growth. Mussel compost, particularly in its early decomposition stages, consistently resulted in poor germination and growth, likely due to ongoing anaerobic decomposition, high sulfur content, and nutrient imbalances. White mustard seeds failed to germinate, while radish and cress showed mixed results depending on the mussel compost treatment. Purchased green compost performed best in multiple tests, whereas Grobruket's garden compost required sieving to improve germination. Even then, success was species-dependent. Fish compost proved unsuitable due to mold growth, poor seedling development, and pest infestations. Similarly, high concentrations of fish compost alone or in combination with sand or coconut fiber prevented germination. Fiber substrates like hortifiber supported good germination, while turbofiber and coconut fiber were less effective. The findings indicate that while some composting treatments enhance aeration and nutrient content, many tested materials remain unsuitable for seed germination without further refinement.

3.2.2 Result of growth performance test

The study compares the growth performance of different composts using cress seeds. Purchased compost had the best growth, followed by sieved Grobruket garden compost. Mussel compost had no germination. Cress grew better in sieved compost than radish, confirming that seed type affects test results.

3.2.3 Compost quality

The study evaluated the compost quality of mussel compost after composting mussels in the Solserv compost machine. The continuous addition of 75% washed mussel shells and 25% wood fiber resulted in a well-aerated but highly nutrient-poor compost, lacking nitrogen and containing only small amounts of phosphorus, potassium, and magnesium, with a higher calcium content. To address the nutrient deficiency, fish waste from herring mixed with wood fiber (2:1 ratio) was added in three stages over three weeks, significantly increasing nitrogen (from 3 mg/l to 572 mg/l), phosphorus (from 25 mg/l to 460 mg/l), and potassium (from 73 mg/l to 1500 mg/l). However, the addition of fish waste led to a strong odor, while also promoting continued microbial activity, as seen in sustained heat production in the compost.

The electrical conductivity rose sharply from 4 to 42 mS/cm, mainly due to increased sodium levels (from 250 mg/l to nearly 1000 mg/l), indicating a need for dilution. Further composting can be conducted with reed and mussel shells (1:2 ratio), to provide a more aerated structure.

4. DISCUSSION

4.1 Havsmineral

The impact of biochar in fertilizer formulations remains a topic of discussion due to its advantages and limitations. One key consideration is that when biochar is charged with ammonium, nitrogen release is slower, reducing its immediate availability to plants. While biochar enhances soil nutrient retention, it may also immobilize nitrogen, potentially leading to short-term nutrient deficiencies unless nitrogen levels are adjusted accordingly. The amount of mineral micronutrients can potentially be reduced or removed given the high levels shown by the outgoing spurway soil analysis at the end of the last study.

Given these mixed effects, further research on biochar's role in fertilizer formulations is necessary before incorporating it into future recipes. If biochar is to be included, increasing nitrogen levels could be a viable strategy to compensate for reduced nitrogen availability. This approach would ensure that plants receive sufficient nitrogen while still benefiting from biochar’s potential to improve soil structure and long-term nutrient retention.

Additional testing of dosage levels can be done together with studies performed on other types of plants to achieve a well-rounded fertilizer that is optimal for many plant species. Furthermore, recipes that exclude kelp products can also be tested.

4.2 Havskompost

The study performed in December 2024 showed that allowing the fish compost to continue the composting process in an open air static pile with passive aeration helped the compost reach a more stable and mature state. The high level of essential nutrients suggests that the compost has potential for use as a long term soil improvement and source of nutrients. However, the high level of sodium can cause salt stress and hinder the uptake of water and nutrients (Machado and Serralheiro, 2017). The large reduction in nitrogen levels during the study indicates that methods to reduce nitrogen leakage are required. Ammonia is released during the acidic composting phase which in turn raises the pH level (Sundberg, 2005). This indicates that the compost has not reached a stable and mature phase (ibid). The results also indicate that longer composting periods are required when using a compost machine in order for the compost to reach a stable and mature state. In the future, the compost recipe can be adjusted to lower sodium levels and increase nitrogen levels. Additionally, future studies can examine alternate inputs to the recipe such as reeds and other organic materials that can improve structure and assist in achieving a stable and mature compost. Future research should focus on optimizing composting processes to reduce toxicity, improve nutrient balance, and enhance substrate stability.

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4.3 Using mussel products in fertilizer and soil amendment products

The plant cultivation experiments showcased advantages and disadvantages of using mussel products as inputs in fertilizers and soil amendment products such as compost.

Mussel shells are rich in calcium and are primarily made of calcium carbonate (Olrog & Christensson, 2003). Persson's study showed that the liming effect of ground mussel shells is comparable to limestone flour as a liming product could replace limestone flour as a liming product (2024). Mussel shells can therefore be used to buffer the pH level of the soil or as an additive to products that would like to achieve this effect (ibid). Additionally, the mussel shells provide an optimal source of calcium for plants due to the high concentration of soluble calcium (Olrog & Christensson, 2003).

Mussel meat is nutrient rich and can also be an additional source of phosphorus, magnesium and potassium (Eurofins Agro, 2024; LMI AB, 2024). The high levels of sodium and sulfur need to be taken into account when incorporating into a fertilizer as to not become toxic to plants.

A complete fertilizer provides plants with all essential macronutrients and micronutrients required for healthy growth and development (Marschner, 2012). Mussel products can be valuable sources of nutrients in complete fertilizers but must be combined with additional organic or mineral nutrient sources in order to achieve a balanced profile that contains all essential nutrients for plants. Havsmineral, is a complete fertilizer and the mussel products are balanced with mineral and organic inputs to achieve an effective and well rounded product. The plant cultivation trials using mussel products performed very well achieving results equal to plants grown with Biomineral and other commercial fertilizers such as Chrysan.

Mussels can be used as compost but a few challenges must be managed for the compost to be an effective soil amendment. These include a lack of nitrogen and high levels of sodium and sulfur. Mussels must undergo a hygienization process consisting of a heat treatment in a closed container before being used in an open air pile (Minnhagen, 2024). The plant cultivation studies showed that seed germination in mussel compost is challenging likely due to ongoing anaerobic decomposition, high sulfur content, and nutrient imbalances. There is potential in using mussel waste products in compost but further trials will need to be performed that mitigate the risks mentioned above.

Waste mussel shells and or mussel meat can be impactful inputs in fertilizers or soil amendment products such as compost while creating a closed-loop system between production and consumption.

5. CONCLUSIONS

5.1 Havsmineral

The Havsmineral recipes have been developed to use sustainable ingredients to reduce waste streams in the sea and on land and repurpose them to provide nutrients to plants. The findings of the cultivation experiments demonstrate that marine-based fertilizers, particularly those incorporating sugar kelp, mussel meat, and biochar, have strong potential as sustainable nutrient sources. However, the dosage level is critical, as lower dosages resulted in chlorosis and reduced plant vigor, whereas higher dosages led to healthy, robust growth.

- Using biochar has potential to impact the release rate of nutrients such as ammonium to help deliver nitrogen slowly over a longer period of time. However, there is a risk that biochar can also be unpredictable and retain too much of the nutrients thus causing nutrient deficiencies. Adding biochar to the recipe would require further studies and evaluation to increase the understanding and proper utilization of its properties.
- Mussel shells and mussel meat have shown to be very suitable inputs to fertilizer products. These products can be effective nutrient sources of calcium, nitrogen, phosphorus and micronutrients such as iron.
- Soil analysis indicates that the amount of mineral micronutrients can be adjusted as a result of using seaweed. Further studies can be done to test this theory.

The most recent recipes using sugar kelp and mussel meat led to positive and promising results. Future studies will test the recipes using other plant species such as flowering and fruit bearing plants. Recipe versions without kelp can also be tested.

5.2. Havskompost

Utilizing mussels in compost has potential but also challenges. Mussels and mussel shells can provide a liming effect and nutrients to the compost. However, the lack of nitrogen and high levels of sodium and sulfur are challenges that must be overcome. The trials showed seed germination was difficult in mussel compost. Incorporating a nitrogen-rich source, such as fish waste along with post-composting has the potential to enhance the composting process and nutrient content of mussel compost. However, several considerations need to be addressed:

- Nitrogen loss and leakage: The risk of nitrogen loss and potential leakage to the environment must be evaluated to ensure efficiency and sustainability.
- Processing of fish waste: The proper handling and treatment of fish waste are essential to prevent odors, contamination, and logistical challenges.
- Post-composting duration: The time required for post-composting needs to be assessed to ensure complete decomposition and nutrient stabilization.

Further investigation is needed to optimize these factors and maximize the benefits of integrating fish waste into the composting process.

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