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Pathways to phase-out contentious inputs from organic agriculture in Europe

Deliverable 5.6

Summary paper on alternative fertilisers

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Authors: *Sabine Zikeli, Carolin Weiler (University of Hohenheim, UHOH), Anne-Kristin Løes (NORSØK), Judith Conroy, Francis Rayns, Dennis Touliatos, Ulrich Schmutz (Coventry University, CU), Krystyna Malińska, Danuta Dróżdż (Politechnika Częstochowska, CUT), Casper Laursen (Innovation Centre for Organic Farming: ICOEL).*

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1. Introduction

Fertilisation in organic agriculture is today highly dependent on the import of external nutrients and organic matter by fertilisers derived from conventional farming and conventional food industries. Within Deliverable 5.1 of the project Organic-PLUS the current use of peat in growing media, plastic for mulching and fertiliser inputs in organic agriculture was already addressed, followed by a report discussing possible alternatives to these contentious inputs (Deliverable 5.2). The current deliverable, 5.6, develops the topic further and shows in more detail the results of research on the use of alternative non-contentious fertilisers conducted in Task 5.4, 'Alternatives to contentious sources of fertility', of Work package 5 SOIL in Organic-PLUS. The objectives of Task 5.4 were a) to characterise relevant alternatives for contentious inputs for physio-chemical and other characteristics (e.g. availability), and study how well they function compared with existing contentious inputs (manure from conventional farming, commercial fertilisers from conventional sources) and b) to develop system approaches to integrate the alternatives in existing organic cropping systems/ sequences. The characteristics of the individual fertilisers as well as short recommendations for their application in practice are presented in the Deliverable Technical Report D5.7. along an overview of nutrient concentrations and other essential characteristics of the fertilisers tested.

Fertilisers derived from conventional farming systems are **considered as contentious for several reasons:** Firstly, the dependency on nutrients from conventional animal husbandry is not acceptable from an organic perspective due to animal welfare issues in intensive conventional farming. Secondly, animal based fertilisers like horn grit are often sourced from countries like Egypt or Pakistan being associated with greenhouse gas emissions for transport, depriving those countries of nutrients that are needed in the country of origin as well. Thirdly, nutrient inputs from conventional animal husbandry systems are often derived from transcontinental feed purchases which opposes one core principle of organic farming, the land-based animal husbandry, leading to major environmental concerns in the countries of feed origin. Last but not least, conventional fertilisers may contain veterinary drugs and pesticide residues, e.g. in liquid vinasse-based fertiliser which contained residues of pyralid, a herbicide used in conventional farming (e.g. McKinnon et al. (2021).

The dependency on nutrients from conventional agriculture is potentially higher for organic stockless arable farms (mainly using conventional manures and composts) and for intensive organic fruit and vegetable producers (mainly using commercial fertilisers permitted in organic farming) as in both cases no internal recycling of nutrients via animal husbandry takes place. In addition, there is a growing number of organic farms that exclude animal husbandry for ethical and environmental reasons, and therefore have the opportunity to use plant-based alternative nutrient sources to improve soil fertility. The interest in alternative fertilisers and fertilisation strategies is growing also as a result of the 25% organic land share target in the European Union stated in the Farm to Fork Strategy of the Green Deal (European Commission 2020) and the 30% target set by the German government and other federal states.

The alternative fertilisers examined in Task 5.4 were selected according to **three different categories:** a) Fertilisers from urban areas which will help to close urban-rural nutrient cycles (category URBAN), b) Plant-based fertilisers, partly with on-farm origin (category VEGAN) and c) Fertilisers derived from organic food industry and organic farms or from sustainable wild collection, such as marine materials (category RESID).

The re-import of nutrients previously exported from organic farms and rural areas serves to close the nutrient gap resulting from the export of (organic) agricultural produce to urban areas. For instance, composts or biogas digestates from source-separated organic household waste can be used as a fertiliser that find acceptance in the organic sector as they are mostly based on food residues that pose relatively little contamination risks in contrast to, e.g. sewage sludge, that is currently not permitted in organic farming. For vegan organic farms which often produce vegetables, legume based-fertilisers as well as other plant-derived fertilisers are a possibility to fertilise the crop sufficiently, as their nutrient content is well adjusted to the nutrient demands of the vegetable crops. Such fertilisation would be compatible with 'Vegan Organic Standards', I.e. the Vegan Organic Network's standards (https://veganorganic.net/wp-content/uploads/Organic-Stockfree-Veganic-Standards-September-2018.pdf) and the Biocyclic Vegan International standards (www.biocyclic-vegan.org/partners/the-biocyclic-vegan-standard) which have become increasingly important in recent years. Residues from organic food production and sustainably produced marine materials are derived from non-contentious sources and are therefore possible alternative fertilisers to fulfil the crop nutrient demands. Currently, such residues are often not used as fertilisers but simply disposed of which can lead to a risk of environmental contamination through an excess of nutrients. By using these fertilisers, the nutrients contained in these residues can be efficiently used for food production rather than being lost, increasing the overall sustainability of the production system.

To test the alternative fertilisers, five partners in five different countries conducted field and pot trials for organic arable farming or horticulture (Figure 1). The selection of alternative fertilisers was strongly based on regional availability of the products.

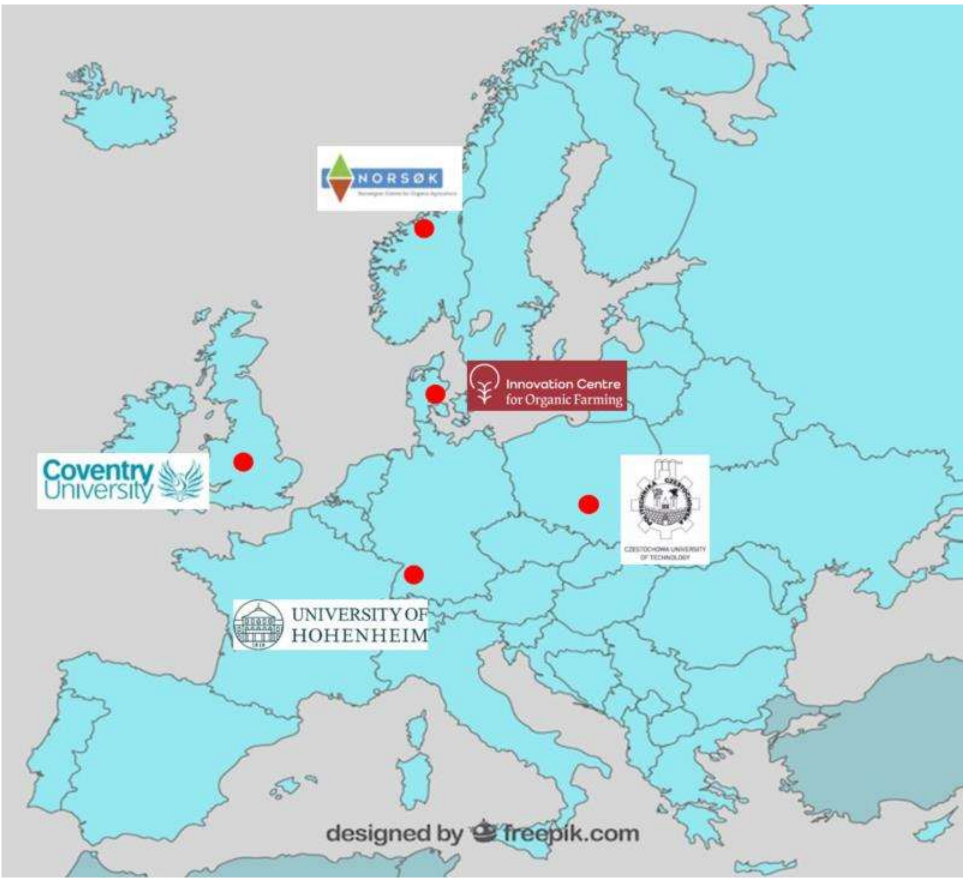

Figure 1: Partners and location of field trial sites used in Task 5.4.

In Denmark, the Innovation Centre for Organic Farming (ICOEL) focused on field trials with biogas digestates from source-separated household waste in organic arable farming. NORSØK, in Norway, conducted field trials using residues derived from captured fish (sediments from hydrolysed, ground fish residues) and seaweed residues from production of seaweed fertiliser extracts in arable farming and perennial leys. In Poland, sediments from freshwater ponds of certified organic fish production were composted and tested as fertiliser in a pot trial by the Politechnika Częstochowska (CUT). Field vegetable trials were conducted by the University of Hohenheim (UoH, Germany) using a system approach to test several alternative fertilisers in an outdoor two-year crop rotation. The following fertilisers were tested: Legume based fertilisers (clover pellets, clover-grass silage, and biogas digestate from clover-grass and pig slurry), digestates of source-separated organic household waste and tofu whey from organic food industry. The effects of liquid plant extracts, and broad bean (*Vicia faba*) flour were examined at Coventry University (CU) in UK for protected indoor vegetable production.

Within work package SOIL Task 5.4 we collaborated and produced two deliverables, D5.7 (technical report), focussing on characteristics of the tested fertilisers and necessary important information of nutrient concentration, applications or possible challenges for application in agricultural practice. This deliverable (D5.6) gives an overview of the results of the fertiliser trials conducted by the five project partners.

2. Current fertilisation strategies and challenges in Organic Farming

2.1 Organic vegetable production

2.1.1 Outdoor vegetable production

In organic farming, nutrient supply and fertilisation strategies are mainly based on the use of legumes for nitrogen (N) fixation. In mixed organic farming systems, ruminants make use of the leguminous fodder plants and nutrients are recycled via animal manure. In organic outdoor vegetable production mixed farming systems are often substituted by stockless farming systems that are characterised by high nutrient exports (Reimer et al. 2020). Such farming systems often rely heavily on external fertilisers either/or as base dressings (manure, compost) or as top dressings (commercial fertilisers permitted for organic farming) even though they often integrate leguminous leys in their crop rotations. However, if legumes, in particular leguminous leys, are grown in stockless farming systems, some farmers might tend to shorten the ley period compared to mixed farming systems as the ley biomass is of no direct economic value as fodder, however it might be used for anaerobic digestion (biogas), clover-grass pellets, clover seed production or just as a greening crop. If the total legume growing is shorted, and not compensated by short-term green manure and catch-crops it could necessitate the import of additional N fertilisers.

Growing vegetable crops in the field is particularly challenging in organic farming as high nutrient levels and adequate timing of nutrient applications are necessary, especially for the cultivation of high and medium demanding crops such as brassica species. In vegetable production, most vegetables are still in full growth when they are harvested. Therefore, a sufficient supply of nutrients must be ensured until the time of harvest in order not to risk any quality defects. However, due to the high fertiliser applications, environmental risks like N leaching and nitrous oxide losses exist, in particular after harvest in late autumn. Therefore, the cultivation of frost hardy catch crops should be considered. Due to high yields of some vegetable crops (e.g. cauliflower, broccoli), large amounts of nutrients are removed from the field and exported from the farm, which can quickly lead to nutrient deficits in the soil. In organic farms with intensive outdoor vegetable cultivation, a sustainable fertiliser strategy is necessary to prevent nutrient imbalances: Vegetables contain large amounts of potassium (K) that is exported and needs to be balanced with external fertilisers while N and phosphorous (P) tend to show surpluses (Reimer et al. 2020). However, this surplus might not always be available to plants, and could potentially leach if it becomes available at a time with no crop demand and high rainfall.

As the number of intensive vegetable farms without livestock increases, it is of growing importance to find alternative non-contentious fertilisers to fulfil the nutrient demand of the crops. Possible options are for example (vegan) plant-based fertilisers like clover grass silage that can be produced on the farm itself or commercially available fertilisers like clover pellets. Fertilisers based on legume biomass are characterised by nutrient contents (narrow N/K ratio) that correspond to the nutrient requirements of vegetable crops while grain legume meals contain higher amounts of P.

2.1.2 Indoor vegetable production

Indoor vegetable production conditions (i.e. polytunnels and/or greenhouses) permit accelerated growth conditions under a controlled environment, which may result in high yields and high crop quality. However, to support these accelerated growth rates, organic growers are required to increase inputs, particularly in terms of soil fertility. These inputs can be in the form of manure, compost, blood meal, bone meal etc., and various liquid organic fertilisers, with the primary aim to increase nitrogen availability to the crops. However, implications may occur as the addition of organic fertilisers can increase the concentration of macro and micronutrients in the soil, some of which might have not been needed. These unwanted inputs are difficult to avoid as all fertilisers used in organic farming are multi-element fertilisers. For instance, (Zikeli et al. 2017) found strong imbalances in nutrient flows in organic greenhouses in Germany. N, P and sulphur (S) were in a surplus while potassium (K) was in a deficit. Overall, the N efficiency of the fertilisers used in the greenhouses was very low. Furthermore, indoor vegetable production is prone to increasing soil alkalinity, salinity and concentrations of plant available phosphorus. The study showed that the current fertilisation strategies in organic greenhouses and polytunnels are not sustainable. The use of green manures in indoor vegetable production could ameliorate these issues. The main challenge here is the difficulty of including green manure crops in rotations in protected cropping because the capital tied up in infrastructure forces farmers to grow as many high value cash crops as possible, often with very restricted rotations. In the UK the excessive import of fertilisers rather than growing green manure crops is quite controversial within the organic movement e.g. the term ‘soil obesity’ has been suggested to describe excessive compost utilisation.

2.2 Organic cereal production

Organic growing of cereals often occurs on farms with limited access to organic animal manure, and thus commercial fertiliser products are widely applied. Often, such products are made from dried poultry manure amended with other materials e.g., vinasse to increase the concentrations of various nutrients and adapt the products to the needs of various crop plants. The edible plant organ in cereals develops after the application of fertilisers to these crops. Hence, they are better suited than leafy crops for utilisation of recycled fertilisers such as hydrolysed proteins and digestates which should not be applied directly to edible crop parts. To keep as many of the nutrients in the system as possible/prevent losses, and to add more nitrogen from nitrogen fixation, organic farmers use pre-crops (e.g. a mustard crop or a undersown green manure crop in a previous cereal) and cover crops extensively. Often, organic farmers are forced into using slurry or manure from conventional livestock which is not desirable and does not fit with the principles of organic farming. Even though these external manures and slurries are used, the plants are often fertilised to a suboptimal level, which restrict yields and thus compromises climate-friendly organic production due to low product outputs per cultivated area. While aiming for more organically farmed agricultural land, other fertilisers/new sources of nutrients are a necessity.

Anaerobically digested source-separated organic household waste (OHW) is a promising material to recycle nutrients and organic matter back to agricultural soils. The source-separation of organic household waste is happening around Europe and if the waste material is digested in a biogas plant, a fertiliser is produced as a by-product of biogas/energy production.

2.3 Current developments in organic farming to adapt fertilisation strategies

Within the EU, nutrient balances in organic agriculture are currently an important and widely discussed topic. This is mainly due to the limited availability of external fertilisers and the use of contentious inputs in organic farming. A number of projects are addressing this subject. These include RELACS (www.relacs-project.eu), DOMINO (www.domino-coreorganic.eu) and NutriNet (www.nutrinet.agrarpraxisforschung.de). In the meta-analysis by Reimer et. al. (2020), nutrient imbalances were observed, although these were strongly dependent on the type of farm and the budgeting method. Generally, an oversupply of N, magnesium (Mg) and sulphur was detected, while the P budget was balanced and K was in a deficit. Similar findings on P were published by Cooper et al. (2018) with a strong dependency for soil extractable P on the country.

For more than a decade, the organic sector has worked hard to reduce the inputs of nutrients derived from conventional production into organic farming systems (e.g. O+ Deliverable 5.2; Bio Austria (2021), Oelofse et al. 2013), to strengthen the integrity of the sector.

Denmark is currently moving forward by integrating recycling materials instead of conventional slurry and manure into Danish organic cropping systems. Agreements with industry are made, so that permitted fertilisers from recycled waste- and residual products are favoured ahead of conventional manure. From 2022 onwards, organic farmers in Denmark are only allowed to use a much smaller amount of manure from conventional livestock, while in addition to organic manure, fertilisers from recycled wastes are allowed to a larger extent. This is not part of the organic legislation, but the agreement covers most of the industry and thus includes every organic farm using animal inputs.

In Germany, the biodynamic growers' association Demeter has gone even further by stipulating in its new standards the phasing out of the use of N fertilisers derived from conventional farming by 2030. However, currently, only limited alternatives for such fertilisers exist.

Therefore, to reduce the dependency on fertilisers derived from conventional animal manure, keratins, slaughterhouse waste or plant-based residues, recycled fertilisers and vegan fertilisation have been given a special attention in Organic-PLUS. Towards the end of this project, with the highly ambitious goals of the recent EU Farm to Fork-strategy aiming at 25% organically managed area in the EU by

2030, the emphasis on recycled fertilisers deserves closer attention. This includes biogas digestate from source-separated organic household waste, and various residual materials from the (organic) food and feed industry. Besides the fertilisers tested in Organic-Plus, struvite (from sewage), which is assumed to become permitted in organic growing towards the end of 2022, should be mentioned here as a source of easily soluble P for organic farming systems. The approval of sewage-based struvite as a fertiliser for organic farming by the EU Commission for the current EU Regulation on Organic Food and Farming could at least partly solve the current P deficits in organic arable farming systems.

3. New fertilisation strategies developed in Organic-PLUS

3.1 The role of system approaches for improved organic fertilisation strategies

The “Rule of Return” as a core principle of nutrient and organic matter supply to the soil within a mixed organic farming system clearly takes a system approach, integrating animal husbandry and cropping systems on farm level. In practice, mixed farming systems often evolve into arable stockless or stockfree/vegan organic farming systems for economic or ethical reasons (Schmidt 2004; Jäckel et al. 2020). In organic fruit and vegetable cultivation a high degree of specialisation on the farm level exists which, in most cases, excludes animal husbandry. In addition, given the fact that mitigation strategies for greenhouse gas emissions require the reduction of animal husbandry, new systems for fertilisation which comply with organic principles are necessary to ensure nutrient supply for organic farms and integrity of organic farming systems at the same time. In Task 5.4 we chose to work with different system approaches at different levels to go beyond a mere substitution of currently used contentious inputs but to consider their acceptability based on the IFOAM principles for organic farming in a wider sense. The first approach (fertiliser category URBAN, Table 1) is based on the attempt to close rural-urban nutrient cycles by using biogas digestates from source separated organic household-waste. Sewage-based struvite is another example of this fertiliser category. The second approach (VEGAN, Table 1) integrates partly on-farm derived plant-based fertilisers such as clover silages or legume meals but also other plant products like comfrey, nettles and clover pellets that can be produced by other organic farms or plant extracts that are home-made and based on plants grown on-farm. Our system approaches that are based on the on-farm-production of fertilisers mainly focus on the integration of legumes as an additional N source in the cropping system. The third approach uses non-contentious inputs from different sources, either organic food industries or organic farms or from **sustainable** wild harvest (e.g. marine derived if this can be done sustainably) or wild collection (e.g. algae from beaches or biomass from nature reserve management) (RESID, Table 1).

Table 1: Categorisation of the alternative fertilisers tested in Organic-PLUS including the location of the field trials, Bold: Final Categorisation of the fertilisers in D. 5.6.

Fertiliser	Category	Country
Clover pellets	**VEGAN**	Germany
Clover-grass silage	**VEGAN**	Germany
Tofu whey	VEGAN, **RESID**	Germany
Biogas digestates (clover-grass & pig slurry)	**RESID**	Germany
Biogas digestates (source separated organic household waste)	**URBAN**	Denmark, Germany
Liquid plant extracts (nettle, comfrey, bean flour)	**VEGAN**	United Kingdom
Pellets/meal made from dried legume foliage or seeds	**VEGAN**	United Kingdom
Sediments from freshwater carp ponds	**RESID**	Poland
Milled residues derived from captured fish	**RESID**	Norway
Seaweed residues from production of liquid fertilisers	**RESID**	Norway

Table 1 shows all fertilisers that were used in Task 5.4 for field and pot trials in detail including the assigned categories and the countries where the trials took place. However, as can be seen from Table 1 the alternative fertiliser tofu whey can be grouped in the category VEGAN as well as in the category RESID. We decided to place it into RESID as the characteristic property to be a non-contentious input from organic food industries is the most important feature of the fertiliser aligning it with the marine products.

3.2 URBAN – Fertilisers from urban sources for organic open field vegetable, protected cropping and cereal production

3.2.1 Biogas digestates from source-separated household waste

In food production nutrients are exported from farms and delivered to urban areas within the agricultural goods consumed there. As a result, large quantities of nutrients are exported from the agricultural systems. These nutrients have to be replaced, usually at high cost, by buying or importing external fertilisers. However, biogas digestates of source-separated organic household waste can return a certain proportion of the nutrients back to the farm. Caution is need with digestate application in organic systems, as in contrast to well composted material digested food waste has a high nutrient availability. This can be a benefit if late fertilising demanding crops and optimise organic yield potentials, it can also be a dis-benefit if applied at the wrong time and contribute to leaching. Digestate is therefore seen as controversial by some the organic movements, as it is 'feeding the plant rather than the soil'.

As a result, the urban-rural nutrient cycle could be closed. In Germany, digestate from source separated organic household waste is easily available. Dependent of the input substrates, biogas digestates have a fertiliser value comparable with cattle slurry (Øgaard et al. 2011). The liquid part of separated digestates, as used in the UHOH trials, is characterised by a low C/N ratio and narrow N/K ratio (Möller and Schultheiß 2014). Furthermore, they contain large amounts of easily plant available N as well as a low P content, similar to the nutrient demands of vegetables. The current EU regulation

2021/1165 permits the usage of source-separated organic household waste as a substrate for composts or biogas digestate, if the concentrations of potentially toxic elements ("heavy metals") are lower than the limits given in the EU regulation 2021/1165 Annex 1.

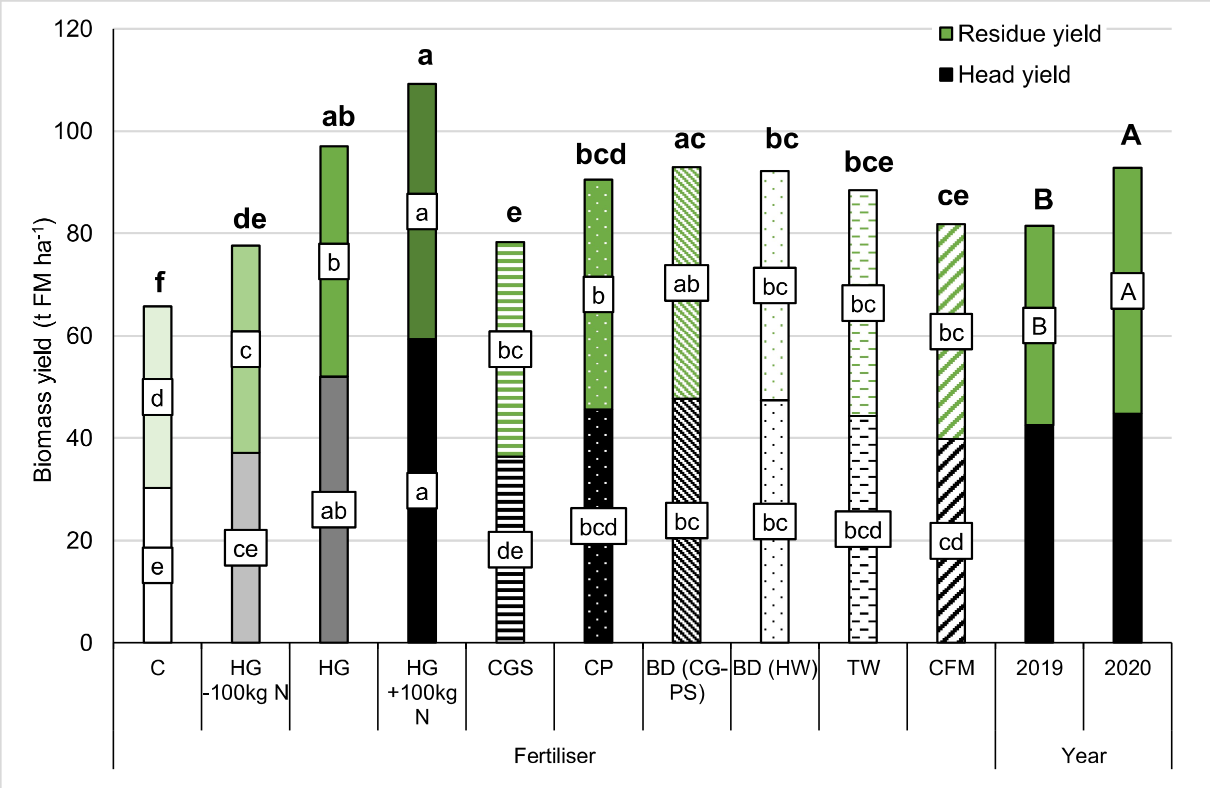

Figure 2: Biomass yield (head and residue) (t FM ha^{-1}) of *Brassica oleracea* convar. *capitata* of ten fertiliser treatments and two experimental years. C=Control; HG= Horn grit; CGS=Clover-grass silage; CP=Clover pellets; BD (CG-PS)= Biogas digestate (clover-grass – pig slurry); BD (HW)= Biogas digestate (household waste); TW=Tofu whey, CFM= Composted farmyard manure, FM= Fresh matter. Lower case letters indicate significant differences among the tested fertilisers and capital letters indicate significant differences between the experimental years for $p<0,05$ (LSD).

When compared to compost from source separated household waste, which is more widely used in organic farming, nutrient availability in particular for N is much higher in digestates due to the high contents of NH_4-N and low C/N ratios resulting from the anaerobic digestion process that consumes easily decomposable organic matter for biogas production. The high contents of easily available N lead to a better timing of N uptake by plants and a higher N use efficiency when using digestates compared to composts or solid manures (Möller 2018). However, in some organic farming associations, in particular in biodynamic farming, the fast availability of N is seen rather critically.

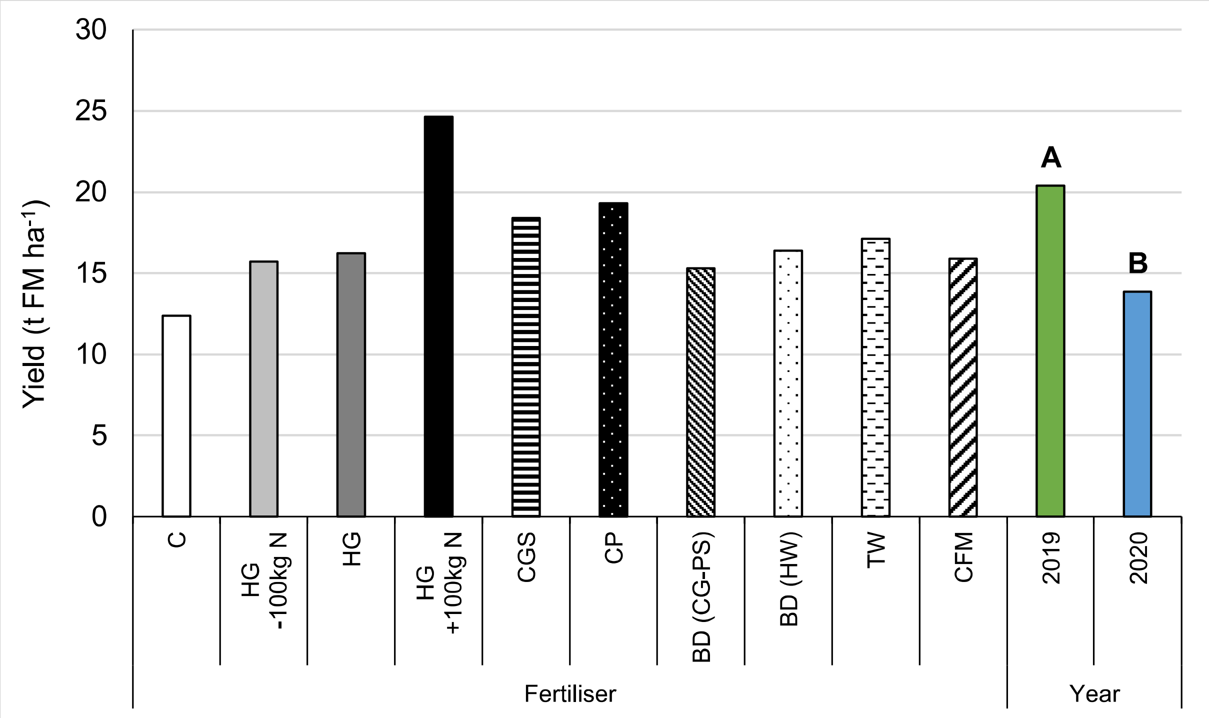

Figure 3: Spinach yield (t FM ha^{-1}) of ten fertiliser treatments and two experimental years. C=Control; HG= Horn grit; CGS= Clover-grass silage; CP= Clover pellets; BD (CG-PS)= Biogas digestate (clover-grass – pig slurry); BD (HW)= Biogas digestate (household waste); TW=Tofu whey, CFM= Composted farmyard manure, FM= Fresh matter. Capital letters indicate significant differences between the experimental years for p<0,05 (LSD).

An important aspect when using biogas digestates from household waste as nutrient source is the quality of the fertiliser. Contaminants such as macro and micro plastics are present and should be monitored closely.

In two field experiments conducted in 2019 and 2020, UHOH tested biogas digestates from source-separated organic household waste in a two-year crop rotation with early cabbage followed by spinach and winter wheat. Cabbage yield of heads (47.4 t FM ha^{-1}) and residues (44.8 t FM ha^{-1}) fertilised with biogas digestate from household waste BD (HW) did not differ significantly from the positive control (the contentious input horn grit (HG) with head weights of 52.0 t FM ha^{-1} and residue of 44.9 t FM ha^{-1}) (Figure 2). In comparison to a second control, composted farmyard manure (CFM) which represents current agricultural practices, the yields of BD (HW) were higher, but did not differ significantly. However, significant differences were determined for BD (HW) and clover-grass silage (CGS), with BD (HW) having a significant higher head and total biomass yield. For the first succeeding crop, spinach (Figure 3), no significant differences are determined for the tested fertilisers. Yield BD (HW) (16.4 t FM ha^{-1}) was on a similar yield level to HG (16.2 t FM ha^{-1}). In the second succeeding crop in the crop rotation, winter wheat (Figure 4), the fertilisers did not differ significantly from each other. BD (HW) showed similar results to CGS (HG: 6.16 t FM ha^{-1} and CGS: 6.14 t FM ha^{-1}), lower yields than HG (6.47 t FM ha^{-1}) and higher yields compared to CFM (5.99 t FM ha^{-1}). Within both experimental years, significant differences have been found with 2020 having higher yields (7.23 t FM ha^{-1}) than 2019 (4.92 t FM ha^{-1}).

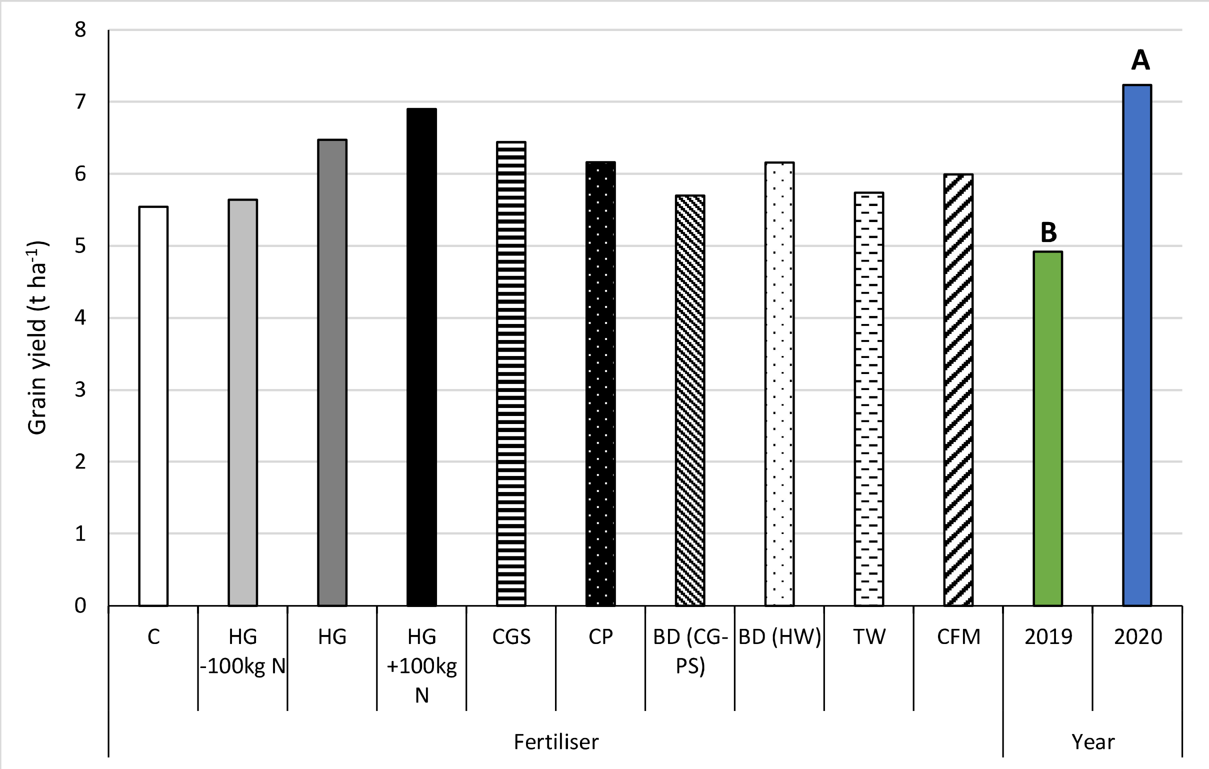

Figure 4: Grain yield of winter wheat (t ha^{-1}) of ten fertiliser treatments and two experimental years. C=Control; HG= Horn grit; CGS= Clover-grass silage; CP= Clover pellets; BD (CG-PS)= Biogas digestate (clover-grass – pig slurry); BD (HW)= Biogas digestate (household waste); TW= Tofu whey, CFM= Composted farmyard manure. Capital letters indicate significant differences between the experimental years for $p<0{,}05$ (LSD).

3.2.2 Recycled fertilisers for organic cereal production

In Denmark, ICOEL tested source-separated organic household waste (HW) and other recycled products as fertilisers in 10 field trials with organic management in spring barley in 2019 and 2020. The digestate for testing in Organic-PLUS was prepared in a pilot plant by the Danish industry partner VARGA, and imported from Germany by another industrial partner (DAKA).

Figure 5: Application of different kinds of biogas digestate including source-separated household waste in one of the field trial, 2019.Photo: Casper Laursen, Innovation Centre of Organic Farming

The trials were conducted on different locations and soil types. The field trials treatments included, among others, products of digestate from 100 % HW and a digestate product containing a mix of HW and cattle slurry. In the field trials, all recycled fertilisers are compared to pig slurry, as pig slurry is known by every organic farmer in Denmark and commonly used in organic farming in cereal production. Also, biogas digestate is applied in the exact same way as slurry (in spring barley, most often by direct injection before sowing) and has the same consistency, and the recognisability of the products gives farmers an easy understanding of the value and usefulness of using HW as a much-needed source of nutrient.

The nitrogen response for the two fertiliser biogas digestates from source-separated household waste (VARGA and DAKA) were comparable to pig slurry. It is shown in Figure 6 together with the other products tested in 2019. For the digestate from HW mixed with cattle manure, the fertilising effect was also comparable to conventional pig slurry in both years (no significant difference in yield when same amount of NH_4-N were applied).Furthermore, in the trials fertilisers derived from slaughtered animals (meat and bone meal; pig bristles) were tested as a positive control (a contentious input). These fertilisers are pelleted and thus suited for early application without risking compaction of the soil. In Figure 6**Error! Reference source not found.**, the yield response for different liquid and solid fertilisers is shown for the growing season 2019. We found a yield increase up to an N fertilisation of 100 kg for the different liquid fertilisers independent from the composition (source separated household waste, pig slurry and mixtures of both). Compared to similar amounts of applied pig slurry, Øgro shows significantly lower yield in spring barley for both application levels.

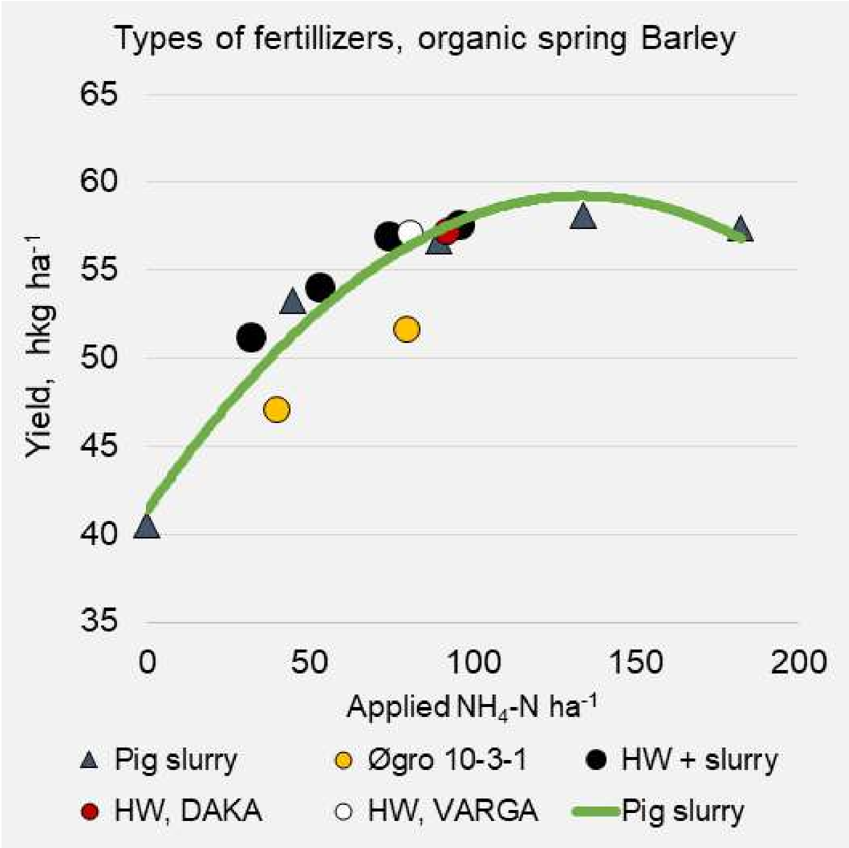

Figure 6: Application of ammonium nitrogen (kg NH_4-N ha^{-1}) and yield (hkg ha^{-1}) with different fertilisers in organic spring barley, 2019.

3.3 VEGAN – Legume-based fertilisers for vegan organic vegetable production

3.3.1 Clover and clover-grass based fertilisers

Intensive organic vegetable farms are in most cases limited in livestock or do not have any livestock. Therefore, nutrients have to be purchased externally or sources within the farm itself. Vegan vegetable farmers can use in their crop rotations clover-grass leys of 1-2 years, to control weeds by mulching the clover-grass, but also for using the biomass as fertiliser either as fresh mulch, as compost or as silage. Clover-grass is particularly suitable as a fertiliser for vegetable production, as the nutrient composition of this fertiliser is very similar to the nutrient requirements of vegetables (high N and K and a low P demand; ratio of N to P and to K) (Möller and Schultheiß 2014). By producing their own legume-based fertilisers on the farm, farmers may influence the nutrient content of the fertilisers as well as the overall N availability within the farming system due to increased rates of N fixation. This also adds to the resilience of the farming system by reducing dependency on external inputs. The C/N ratio can be influenced by the proportion of clover to grass and the time of cutting (Möller and Schultheiß 2014). Vegan clover pellets can also be purchased. At the time of purchasing the fertilisers for the trials in UHOH the price for clover pellets with approximately **20 € per kg N** was expensive when compared to horn grit (6-7 € per kg N). However, the producer of the clover pellets expects a price reduction in the next few years due to improvements in production and economy of scale.

Within the field experiments at UHOH, head and total biomass yields of cabbage fertilised with clover pellets (Head: 45.6 t FM ha^{-1}; Total: 90.5 t FM ha^{-1}) were lower but not significantly different to the control with horn grit (Head: 52.0 t FM ha^{-1}, Total: 97 t FM ha^{-1}) (see Figure 2; Section: 3.2.1). In contrast to the clover pellets and the horn grit treatment, clover-grass silage achieved the lowest yields of all fertilisers with head yields of 36.4 t FM ha^{-1} and a total biomass yield of 78.3 t FM ha^{-1}. These yields are on the same level as a fertilisation with 100 kg N less compared to the standard horn grit fertilisation (positive control, contentious input). For the following crop, spinach, no significant differences were found for all treatments (see Figure 3**Error! Reference source not found.**; Section: 3.2.1). On average, the yields in the first succeeding crop in the treatments with clover-grass-based fertilisers were higher than those that were fertilised with horn grit or farmyard manure; similar results were found for the other alternative fertilisers. Within the clover-based fertilisers, clover pellets seem better able to supply nutrients to the second crop (spinach), as the yields were slightly higher compared to silage. The third crop in the crop rotation (winter wheat) showed no significant differences in grain yields (see Figure 4; Section: 3.2.1). The yields of the fertiliser treatment with clover-grass silage, with 6.44 t ha^{-1}, were at the same level as when fertilised with horn grit (6.47 t ha^{-1}). Furthermore, it was higher than the yields of the other alternative fertilisers including the clover pellets (6.16 t ha^{-1}).

3.3.2 Comfrey, nettle and bean fertilisers for intensive protected tomato production.

Researchers at Coventry University (UK) conducted a polytunnel trial to assess the sustainability and practicalities of plant-based fertilisers for the commercial production of organic tomatoes. The raw materials for the fertilisers were leaves and stems of comfrey (*Symphytum* spp.), stinging nettle (*Urtica dioica*) and broad bean (*Vicia faba*) flour. These were compared against water (zero control) and against a commercial organic liquid feed (Ilex High fruit 4-2-6); which was based on conventional sugarcane molasses (this is used as a positive control, as it is not produced *on-farm* and is a fertiliser derived as a by-product from conventional farming and so seen as contentious by some).

‘Stock-free farming’, ‘vegan organics’ or ‘veganics’ are promising approaches for phasing out the use of manure from organic horticulture as they exclude all animal husbandry and husbandry products for ethical reasons (Schmutz and Foresi 2017). This is in contrast to stockless organic farming systems: In these systems, farmers are not keeping livestock for e.g. economic reasons, labour issues or own interest, but external animal-based fertilisers are purchased or brought in through a cooperation with neighbouring livestock or mixed farms exists to exchange fodder and manure.

However, the efficacy, sustainability and practicalities of these strictly vegan approaches have not yet been investigated in depth. Collecting and disseminating robust scientific evidence concerning vegan organic approaches could inspire organic and non-organic growers to adopt these methods and minimise the use of other animal products for growing crops, thus mitigating the risks associated with contentious fertilisers. Importantly, the trial explored the practicalities of producing the raw materials for the plant-based fertilisers on-farm.

Figure 7: Comfrey plants were grown next to the polytunnel and were exploited to provide nutrients for the tomato trial, enabling on-farm nutrient acquisition for intensive organic protected cropping.

The trial was conducted in 2020 at the experimental site of the Centre for Agroecology, Water and Resilience, Coventry University at Ryton Organic Gardens in an unheated polytunnel covered with polyethylene film. The polytunnel was constructed in 2019, the soil was a sandy loam - it had been covered with polypropylene mulch for five years and prior to the trial the polytunnel was then sown with a combination of rye and vetch used as winter green manures. All above ground biomass was removed from the polytunnel and a rotavator was used to prepare the ground for tomato cultivation. Automatic irrigation was delivered via drip irrigation tape. The researchers explored the potential of different vegan organic approaches in building soil fertility as well as how practical it is for growers to produce their own liquid feeds in contrast to using off-the-shelf commercial vegan crop feeds. The trial was conducted within a semi-commercial context, in collaboration with the stock-free CSA ‘5-Acre Community Farm’ on site; to further reinforce the realism of the trial.

The comfrey and nettles were chopped and then steeped in water for four to six months. The concentrated liquid was then sieved to 10mm and diluted with water to create a liquid feed for the plants (Figure 8).

Figure 8: Comfrey stems and leaves were harvested on-farm and steeped in water within airtight barrels for 4-6 months to create a liquid feed.

Figure 9: The trial set up at the polytunnel at Coventry University, Ryton Organic Gardens. Strings demarcating the plots can be seen. (n=4)

The bean flour was suspended in water and slowly became incorporated into the soil as the crops were watered. It was anticipated that the high nitrogen content of the broad bean flour, which was then locked into proteins, would be slowly released and made available to the plants as the proteins broke down through microbial activity in the soil. The high user-friendliness of the bean flour approach compared to the comfrey and nettle liquid fertilisers, as well its potential to contribute to the reduction of crop waste by using beans that would have been otherwise discarded, was noted.

Tomatoes (*Lycopersicon esculentum*) cv. 'Douglas' were transplanted on 22/5/20 and supported by strings. They were pruned as required to maintain a single leading stem with five fruiting trusses in a high-wire commercial system. Fourteen weekly harvests of ripe fruit were made between 5/8/20 and 4/11/20; there were ten weekly applications of feeds made from 31/7/20.

The application rates were standardised according to the total nitrogen content, recognising that according to Soil Association regulations at least half of the nutrients must come from the soil rather than supplementary feeding. Two treatments were applied: the LOW treatment, which supplied 73 kg N/ha and the HIGH treatment which supplied 146 kg N/ha (Figure 9).

Weekly harvests of ripe fruit were made over a 14-week period. Figure 10 shows the total weight of tomato fruits from each treatment. There were no significant differences and variation was similar between treatments, which indicate that plant growth and crop productivity were not affected by the treatments; instead, the plants exploited the soil fertility within the polytunnel in a balanced manner.

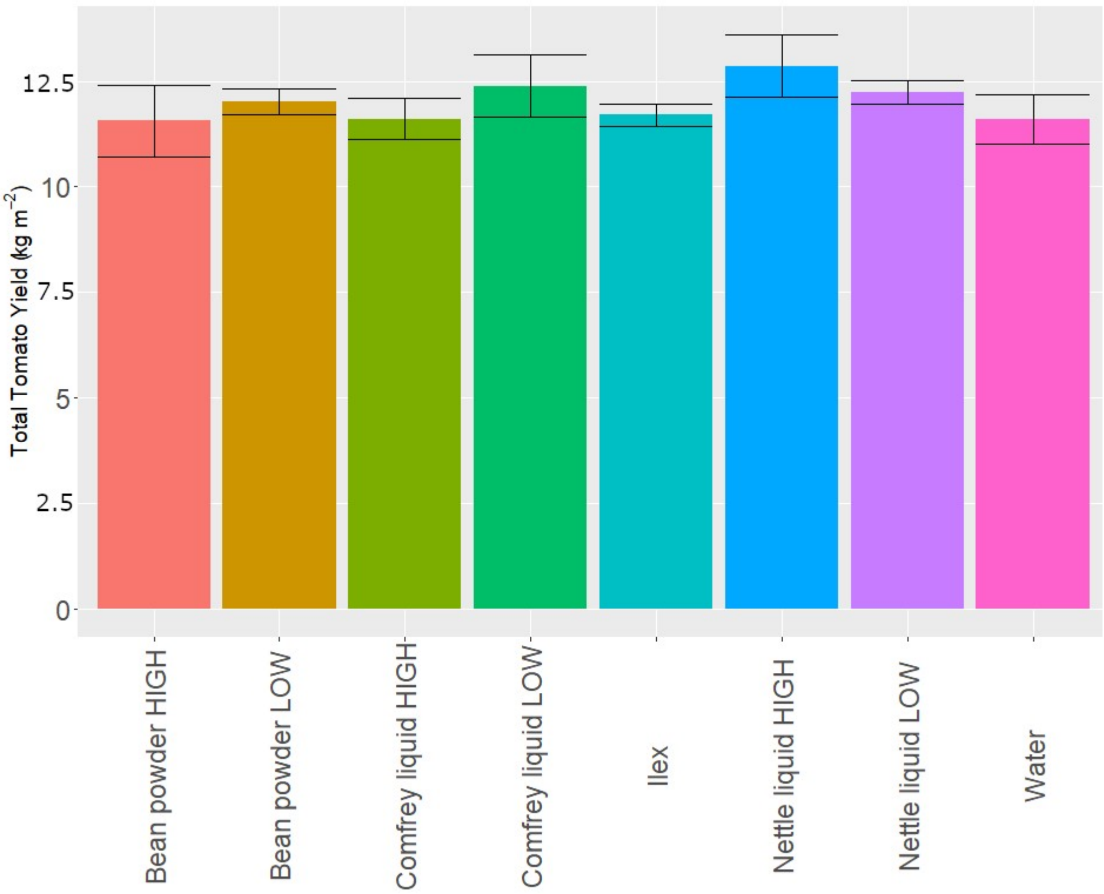

Figure 10: Total tomato yield per treatment harvested over a 14-week period. Water treatment is control. Values are the means of four replicate plots and vertical bars indicate SE, standard error of the mean (n=4).

Importantly, the average tomato yield per square meter for the whole polytunnel for all treatments combined was 12 ± 1 kg m^{-2}, which is relatively close to the reported average tomato yield for unheated polytunnels in the UK, which is 14.8 kg m^{-2} (Schmutz et al. 2011).

Although there were no significant differences in tomato yield between treatments the effects of some of the fertilisers could be seen in the soil. This was the case even six months after the final application of vegan fertilisers; soil mineral N concentrations were lowest in the control plots (Figure 11). Soil nitrogen mineralisation increased after the removal of the tomato crops in the autumn and the available nitrogen was effectively utilised by the following *Phacelia tanacetifolia* green manure crop grown.

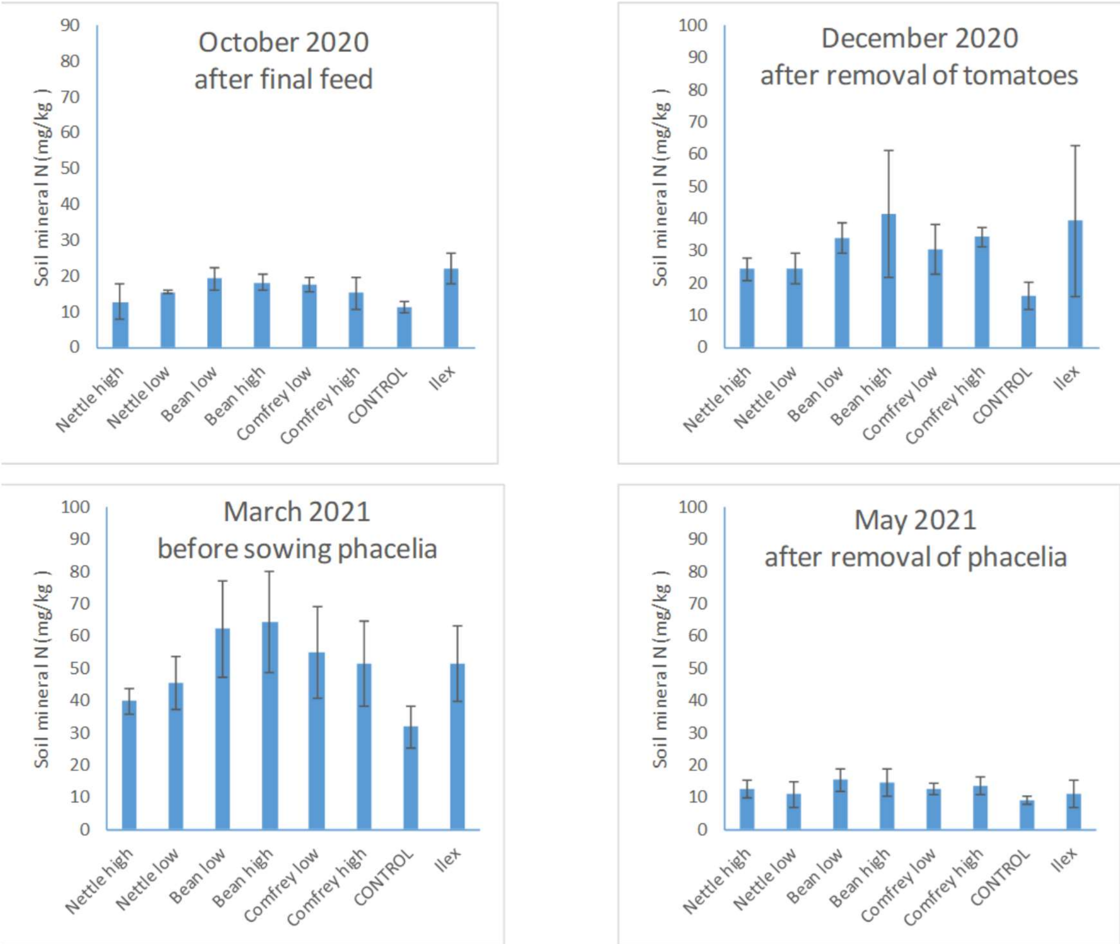

Figure 11: Soil mineral nitrogen sampled at 0-15cm from soil surface. Means of four replicates +/- standard deviations.

Taken together these data indicate that the background levels of nutrients fertility in this experiment were too high to demonstrate a beneficial effect of feeding on the yield of tomatoes. Importantly, this confirms that organic production, even in intensive cropping, need not rely on short-term additions of nutrients. On the contrary, soil fertility in organic production systems, particularly in intensive protected cropping, should be based on long-term planning. This is a strategy focussing on 'feeding the soil rather than plants' and exploring how plant-based strategies such as green manures and vegan fertilisers can provide adequate nutrients for the production of high quality organic crops. The December Nmin data (double of control) might suggest that there is N loss potential with high rainfall in winter. This is however a greenhouse situation, but even in an open field situation a winter cover crop like grazing rye (*Secale cereale*) could capture this and make it available in the following year. Further research is ongoing to investigate the carry-over of soil fertility and specifically N in this experiment.

3.4 RESID – Fertilisers from non-contentious external sources

3.4.1 Marine-derived fertilisers

Elements from terrestrial environments, such as phosphorus (P) which is a scarce resource and crucial for agricultural productivity, are leached to the sea. In many areas, especially near the coast, seawater is enriched in nutrients, leading to high production of organic matter, which may lead to oxygen deficiency during decomposition. Hence, it may be an environmentally friendly fertilisation strategy to apply nutrients to agricultural soils, which are derived from the sea, provided they can be harvested in a sustainable manner. Harvesting nutrients from natural sources, e.g. by grazing, is well in line with organic principles. In Norway, the capture of wild fish is a significant industry. Residual materials from captured fish, which usually are food quality materials (Category 3 animal by-products (European Commission) https://ec.europa.eu/food/safety/animal-products_en) may be more applicable in organic growing. Most fish-based materials, being rich in fat and/or proteins, are utilised for food or feed (e.g. in aquaculture), but fish bones are commonly poorly utilised (Ahuja et al. 2020) and contain high concentrations of valuable plant nutrients such as N, P and calcium (Ca). Another relevant resource is seaweed, in particular brown algae. Brown algae (e.g. *Ascophyllum nodosum* as used for the algae fibre in the Organic-PLUS trial) are very common along the Norwegian coast, and already harvested in significant amounts for various purposes such as producing seaweed extracts for fertilisation and alginate for industrial purposes. This leads to residual materials with high concentrations of valuable macronutrients for plants such as K, Mg and S. There is also a great interest in seaweed cultivation, which will also lead to residual materials. When applied in combination, fish bones and algae fibre could possibly be a complete fertiliser covering the demand of these six macronutrients for crop plants. For fertilisation purposes, the cost of materials applied must be low because nutrients in fertilisers are generally very poorly valued per amount of nutrient, as compared to nutrients in animal feed and food for human consumption. Hence, residual materials, which currently induce costs for the industry to handle, are relevant for fertiliser production. Currently, algae fibre is incinerated in spite of a dry matter content of only 25-30%, and fishbone residues, which may be applied for feed for fur animals (a risky and declining market) are incinerated or sometimes indirectly dumped at sea e.g., by cutting off fish heads during capture.

With this background, and with a location nearby the fish and seaweed industry, NORSØK has been working with marine-derived fertilisers for organic growing since 2017, supported by funding from Møre og Romsdal county municipality (MRCM) but also from other sources, such as Horizon 2020 GA 774340 (Organic-PLUS) and since 2021, funding from the ERA-net BlueBio2 for the project "MariGreen" (Parvulescu et al. 2021) The funding from GA774340 made it possible to expand one year of field trials funded by MRCM to two seasons of field trials, and to expand the volume of chemical analyses of fertilisers, soil and plant materials.
further details: https://bluebioeconomy.eu/wp-content/uploads/2021/07/BlueBio_MARIGREEN.pdf.

An initial study of ryegrass growth in pots in a controlled environment, and the effects of applying marine-derived fertilisers (Ahuja and Løes 2019) revealed that fish bones had a very rapid effect on plant growth and increased the production of ryegrass significantly. Algae fibre had a much slower effect, but increased plant growth towards the end of the study. In total, across two N levels, the grass yield over five harvests (stubble included) was 3.3 g DM per pot for fish bones, as compared with 2.2 g DM per pot in the unfertilised control. Fertilisation of ryegrass with either algae fibre or calcium nitrate both gave an average yield of 2.6 g DM per pot. Converting these numbers to t DM/ha the accumulated yields were 7.2 with no fertiliser (relative value = 100%), 8.5 with algae fibre (= 119%), 8.6 with calcium nitrate (= 120%) and 10.9 with fish bones (= 152%). Slightly more N was applied with calcium nitrate than with fish bones, and the additional yield effect may be explained by fishbone P since the test soil was low in P. Fertilisation with algae fibre led to luxury uptake of K. In spite of high concentrations of arsenic (As) (33 mg/kg DM) in algae fibre, the concentrations of As in the ryegrass plants amended with this material were below the limit of detection.

In field experiments, fish bones and algae fibre were tested in oats in 2019 and in ryegrass with 4 cuts in 2020. In 2019, an outdoor pot experiment with oats and leek was conducted, too, where pots were filled with sieved soil from an area adjacent to the experimental oats plots and then buried in field soil and subject to natural field conditions. The field plots with oats and ryegrass were located in the same field with about 100 m distance between 2019 and 2020 plots. Soil from this field was also used in the pot experiment with ryegrass mentioned above.

Outdoor experiments confirmed the initial results from the ryegrass pot experiment: Fish bones have an immediate growth effect, whereas algae fibre have a slow effect. However, as a perennial grass-cover ley was sown under the oats in 2019, residual effects of the application of marine-derived fertilisers were studied in 1st year ley in 2020, and 2nd year ley in 2021, with no application of fertilisers since 2019. In 2020 and 2021, the residual effect of algae fibre was significant: Total yields (with two cuts) increased from 4 to 6 t ha^{-1} of dry matter in 2020, and from 5 to 16 in 2021 (Figure 12). A positive residual effect of algae fibre was also observed in potatoes grown in 2021 on the experimental plots where ryegrass was grown in 2020 (Løes et al. 2022). The concentrations of As in the potatoes grown in soil where algae fibre was applied in 2020 were not higher than in potatoes grown in soil amended with other fertilisers (fishbone materials or dried poultry manure).

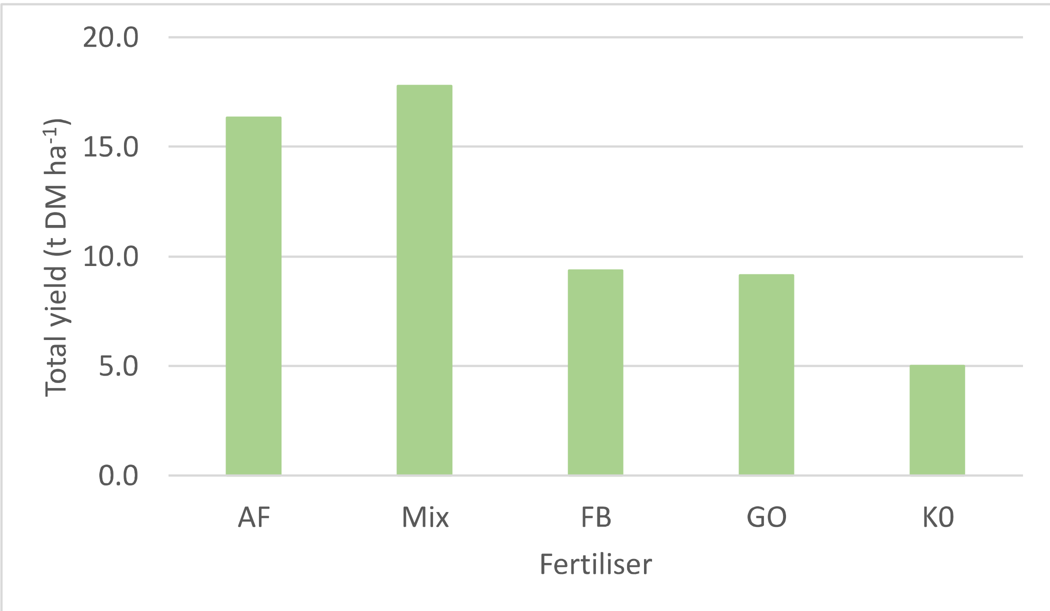

Figure 12: Total yield (sum of two cuts) in 2021 of a grass-clover ley established in 2019, fertilised with 160 kg N/ha in algae fibre (AF), grinded fishbones (FB), dried poultry manure, commercial product named "Grønn Øko" (GO), or a mix of AF and FB where 70% of N was derived from FB (Mix), as compared with a unfertilised control (K0). No fertiliser was applied in 2020 or 2021.

3.4.2 Biogas digestates – clover-grass and pig slurry based

Within organic agriculture, even stockless farms without animals include clover-grass or other leguminous crops in their crop rotation for nitrogen fixation and for weed control (Benke et al. 2017). Ideally, the clover grass cuts could be used for animal feed or a feedstock in a biogas plant in a cooperation between organic farmers. Within the fermentation treatment, clover-grass biomass can be used for energy production with low N-losses (Möller and Müller 2012). When produced within the farm itself, a mobile N-fertiliser is produced and nutrients can be reallocated within the farm (Möller and Stinner 2009)

The results of the field experiment at UHOH showed significant differences for the tested alternative fertilisers (see **Error! Reference source not found.**Figure 2; Section: 3.2.1). For biogas digestates with clover-grass and pig slurry the highest cabbage yields (Total: 92.9 t ha^{-1} and Head: 47.7 t ha^{-1}) of all tested alternative were determined. The yields differed not significantly from a fertilisation with horn grit (Total yield: 97.0 t ha^{-1}; Head: 52.0 t ha^{-1}) and farmyard manure (Total yield: 81.8 t ha^{-1}; Head: 39.8 t ha^{-1}). However, yields of clover-grass silage were significantly lower compared to the biogas digestate. Even though there were no significant differences among the fertilisers for the first succeeding crop (spinach) (see **Error! Reference source not found.**; Section: 3.2.1), the yield of the biogas digestate treatment (15.3 t ha^{-1}) was 0.9 t ha^{-1} lower compared to horn grit and 0.6 t ha^{-1} than farmyard manure. For winter wheat, grain yields showed similar results than spinach yields (see Figure 4; Section: 3.2.1). The yields of biogas digestates were lower than in the treatment with horn grit (6.47 t ha^{-1}, positive control, contentious input) and farmyard manure (5.99 t ha^{-1}).

3.4.3 Tofu whey

During the production of food, residues are produced that have to be disposed of by the companies and thereby cause additional expense. However, these residues still contain valuable nutrients that are lost in the disposal process. By recycling these residues, the nutrients present in the residual product could be used for fertilisation in agriculture. One of these residues is tofu whey, which is produced during tofu production and, currently, has to be disposed of by the manufacturers. Due to its low P and high K content per kg N, tofu whey is particularly suitable for use in organic vegetable production. Since there is usually a P surplus due to the use of manure, this can be reduced or even compensated for by adjusting the fertiliser management using a combination of different fertilisers. The problem when using tofu whey is the high water content of approximately 98% resulting in a low N content in its fresh mass. The high water content is a major problem for the use of organic fertiliser in vegetable production, as large quantities of whey would have to be transported to fulfil the high nutrient requirements (especially N) of the vegetables. Therefore, further technological progress is needed to reduce the water content and thus lower the transport costs per kg N. Before using tofu whey, the relevant authorities have to give permission for its use in organic farming. In addition to the origin of tofu whey production, it is important to clarify with the control body whether the coagulants used for tofu making (Nigari, a natural coagulant from saltwater, and calcium sulphate) are approved as fertilisers for organic farming.

Within our study, total biomass yield and head yield of cabbage fertilised with tofu whey did not differ significantly from the standard fertiliser horn grit and composted farmyard manure (see Figure 2; Section: 3.2.1). Overall, the yields in the horn grit treatment (97.0 t ha^{-1}) were higher than those of tofu whey (88.4 t ha^{-1}) and composted farmyard manure (81.8 t ha^{-1}). In comparison to the other alternative fertilisers, only total biomass yield of clover-grass silage differed significantly from tofu whey and showed lower biomass yields (78.3 t ha^{-1}). For the first succeeding crop spinach no statistically significant differences were found (see Figure 3; Section: 3.2.1). However, yield of the tofu whey treatment with 17.1 t ha^{-1} was higher than horn grit (16.2 t ha^{-1}) and farmyard manure (15.9 t ha^{-1}).

The second succeeding crop winter wheat showed also no significant differences among the tested fertilisers (see Figure 4; Section: 3.2.1). Fertilisation with tofu whey resulted in yields that were higher than those of composted manure over the 2-year vegetable crop rotation, however, the difference was not significant. Furthermore, fertilisation with the residue was able to provide a similar, but slightly lower yield level within the crop rotation compared to horn grit.

3.4.4 Organic fish pond sediments

Organic fishpond sediments (FPS) are a mixture of fish waste, decaying plants, algae residues, uneaten feed, sand and some marine microorganisms. The sources of nutrients in fresh water fishponds include fish feed, organic, and inorganic fertilisers. Characteristics of FPS differ depending on many factors including the type of aquaculture system (organic, conventional), type and age of fish, water quality, feeding type and regime, weather conditions, etc. Also, these factors can have an impact on the quantities of FPS generated during the process and removed from the fish farming systems (Dróżdż et al. 2020b).

Organic fish sediments are also a valuable source of different organic compounds that can be used in various technological processes. Organic FPS are characterised by pH 6-7.7, N 1.08-7.03 g kg^{-1}, C 18.3-92.3 g kg^{-1}, K 0.62–2.25 g kg^{-1} and P 0.22–2.07 g kg^{-1}. They can be used, among others ways, by composting (Dróżdż et al. 2020a). The composting potential of organic FPS was tested as part of the Organic-PLUS project by members of the research team from CUT. The aim of this work was to investigate at a laboratory scale the potential of FPS for composting with selected waste materials and to analyse the resulting compost and compost mixtures for soil fertilisation. The scope of this work was (A) Physical and chemical analysis of initial material (organic FPS), (B) Laboratory composting, (C) Physical and chemical characteristics of obtained composts, (D) Preparation of compost mixtures and the analysis of selected properties, (E) Preparation of growing media by mixing soil with the compost mixtures and the analysis of selected properties, (F) The analysis of the impact of compost mixtures on growth and yield of *Phaseolus vulgaris* L., a test plant. The hypothesis of this work was that compost from organic FPS from trout farming can serve as a fertiliser.

The research experiment was started with the process of composting fishpond sediment from certified organic trout aquaculture (Location: Złoty Potok, Silesian Voivodeship, Poland), which was mixed with wheat straw (from conventional farming) and grass (from a domestic garden, no mineral fertilisation). Three composting reactors were equipped with a leachate aeration and a drainage system (Dróżdż et al. 2020a). Fresh organic fish pond sediments were mixed with wheat straw and freshly mown grass. The characteristics of the substrates which were used for composting are presented in Table 2.

Table 2: Characteristics of composting substrates.

Substrate	pH	MC	OM	TN	TOC	C/N
Units	-	%	%	%	%	-
FPS	7.6	63.48±1.72	30.38±2.13	0.41±0.18	10.19±0.45	25
Fresh grass	6.3	64.36±1.37	92.32±0.80	1.46±0.12	36.29±0.08	25
Wheat straw	6.6	8.25±2.12	95.80±0.61	0.45±0.08	36.84±0.43	82

*MC-moisture content; OM-organic matter; TN- total nitrogen; TOC- total organic carbon; ratio C/N-carbon/nitrogen.

The use of straw and grass resulted in an improvement in the porosity of the compost mixture. This treatment also made it possible to improve the airflow in the compost bioreactor. The additives in the form of grass and straw also increased the organic carbon in the mixture which is essential for the microorganisms. They consume about 15-20% during the entire composting cycle (Huang et al. 2004)

The composting process was carried out for 4 weeks, the temperature was measured daily. The highest temperature of the process was obtained in the first week of composting (day 4), around 52°C. The compost began to stabilise around day 12 of the process. The temperature remained at 22°C. This meant that the active phase of composting was over. After 4 weeks the composting process was completed (Eymontt et al. 2017).

After 4 weeks of composting, the compost was removed from the bioreactor. Then it matured for several weeks at room temperature (around 21°C). The next step was to prepare compost mixtures. In order to check the compost potential, the compost was mixed different organic materials: cardboard (M1), biochar from wood chips (M2), and a combination of cardboard and biochar from wood chips (M3). Table 3 shows the proportions of the compost mixtures. The physicochemical analysis of the obtained compost was also carried out (Table 4) .

Table 3: Proportion of composting mixtures.

Ratios of mixtures	**Compost mixtures**		
	Compost from FPS with cardboard - Mixture 1 (M1)	**Compost from FPS with biochar from wood chips - Mixture 2 (M2)**	**Compost from FPS with cardboard and biochar from wood chips - Mixture 3 (M3)**
	(CFPS:C)	**(CFPS:B)**	**(CFPS:C:B)**
Dry weight	1:0.09	1:0.02	1:0.09:0.02
Wet weight	1:0.06	1:0.01	1:0.06:0.01

Table 4: Characteristics of composts and composting mixtures before, during and after 4 weeks of the process.

Parameters	pH	MC	OM	TOC	TN	P_2O_5	C/N
Units	-	%	%	%	%	mg g^{-1}	-
Start of composting	7.06	72.25±1.41	51.34±2.84	19.56±0.06	0.95±0.28	136.88±0.01	21
Composting after 2 weeks	8.21	75.39±1.00	37.43±3.43	18.36±0.22	1.32±0.20	120.12±0.01	14
End of composting	8.54	71.64±2.55	32.56±3.58	17.42±0.49	1.43±0.16	147.36±0.01	12
Compost mixtures (M1)	8.55	70.35±1.52	41.78±3.19	19.74±0.71	1.26±0.12	113.66±0.01	16
Compost mixtures (M2)	8.64	72.73±0.87	39.31±0.88	18.37±0.44	1.23±0.20	126.41±0.01	15
Compost mixtures (M3)	8.53	71.21±1.10	40.70±0.69	19.66±0.23	1.16±0.18	115.41±0.01	17

*MC-moisture content; OM-organic matter; TN- total nitrogen; TOC- total organic carbon; ratio C/N-carbon/nitrogen; ± standard deviation.

A typical compost has a C/N ratio of 15. The organic fishpond sediment compost had a C/N ratio of 12. Over time, the nitrogen content and pH of the composts increased. On the other hand, the content of organic matter and organic carbon, which was partially used by microbial organisms in the compost, decreased (Iglesias Jiménez and Pérez García 1992; Piotrowska-Cyplik et al. 2013).

The next step was to mix the compost and compost mixtures with the soil. In the pot experiment were 5 soil combinations were used in the process. Soil (from agricultural fields in the vicinity of Częstochowa (Poland), texture: loose and weakly loamy sand) as control, growing medium 0 (soil + compost from FPS + cardboard), growing medium 1 (soil + compost from FPS + cardboard), growing medium 2 (soil + compost from FPS + biochar from wood chips), growing medium 3 (soil + compost from FPS + cardboard + biochar from wood chips). Five replications were made for each of the soil mixtures (ratios soil: compost/compost mixture) are shown in Table 5

Table 1.

Table 5: Ratios of compost/composting mixtures vs. soil for the treatments (compost, composting mixtures, soil) for pot experiment.

Ratios	Treatments			
	Growing medium (GM 0)	Growing medium 1 (GM 1)	Growing medium 2 (GM 2)	Growing medium 3 (GM 3)
	(Soil:Compost)	(Soil:M1)	(Soil:M2)	(Soil:M3)
Dry weight	1:0.03	1:0.03	1:0.03	1:0.03
Wet weight	1:0.07	1:0.07	1:0.07	1:0.07

Figure 13: Growth and yield of Phaseoleus vulgaris L. after 2, 4 and 12 weeks (Growing medium 2).

Figure 13 presents photos of plants with the highest increase in plant biomass. Growing medium 2 showed the best performance, as it was the only mixture in which 5/5 seeds germinated. After the plant growth period, the soil mixtures were re-tested to see what changes occurred in the soil after 12 weeks. The results are presented in Table 6.

Table 6: Properties of the investigated growing media after completion of the pot experiment.

Parameters	pH	MC	OM	TOC	TN	P_2O_5	C/N
Units	-	%	%	%	%	mg *g^{-1}	-
Control (Soil)	6.82	0.43±0.36	3.98±0.09	2.39±0.14	0.13±0.01	36.53±0.06	18
Growing medium 0	7.83	0.22±0.08	5.67±0.37	3.56±0.19	0.21±0.01	58.84±0.03	17
Growing medium 1	8.08	0.21±0.11	5.54±0.17	3.53±0.11	0.20±0.02	74.38±0.01	18
Growing medium 2	8.09	0.41±0.35	6.06±0.29	4.06±0.11	0.21±0.01	66.03±0.08	19
Growing medium 3	8.06	0.58±0.40	5.57±0.32	3.99±0.31	0.20±0.01	56.01±0.03	20

*MC-moisture content; OM-organic matter; TN- total nitrogen; TOC- total organic carbon; ratio C/N-carbon/nitrogen; standard deviation.

The contents of heavy metals in the tested materials (organic fish pond sediments, straw, grass, and soil) were not exceeded according to the Ordinance of the Minister of Agriculture and Rural Development of June 18, 2008 (Rozporządzenie Ministra Rolnictwa i Rozwoju Wsi, 2008).

Organic fishpond sediments from trout farming demonstrate potential as fertilisers. The compost obtained from fishpond sediments was characterised by a relatively low content of organic matter and organic carbon compared to typical composts. This is mainly due to the higher content of mineral matter (i.e., sand). Therefore, compost from organic fishpond sediments should be supplemented with materials that could increase the organic matter and organic carbon content and enable water and nutrient retention.

Mixing compost with cardboard and biochar increased the content of organic matter, P and total C. The addition of biochar from wood chips to the finished compost has positive effect on the growth of *Phaseolus vulgaris* L.

Fishpond sediments and their potential to fertilise the soil are not well described in the literature. More research is needed to understand how various factors such as fish type, farming system, feed, seasonality, pond management, etc. affect the sediment composition of fishponds. However, composting of organic FPS can certainly be an alternative to storing or land spreading.

4. On-farm application – potentials and challenges

The results of the trials on alternative fertilisers conducted in WP 5 showed that all fertilisers in the three categories URBAN, VEGAN and RESID can substitute the contentious inputs currently used in organic farming as they resulted in similar yields to the standard fertilisers from conventional farming that were used as positive controls in the trials. However, the different fertilisers each have different strengths and weaknesses compared to the currently used fertilisers (Table 7).

In case of clover grass silage and algae fibres, which resulted in lower yields in the first main crop but showed improved yields in subsequent crops in the rotations, adaptions of the fertilisation management (e.g. earlier application to improve timing of N release or combinations with other fertilisers in the first year of application) may further improve their usability as a fertilisers. When introducing new alternative fertilisers into organic cropping systems, such adaptions in fertilisation strategies have to be taken into account and further research is needed to optimise such system-based fertilisation approaches that do not just focus on the main crop but include multiple cropping years. In addition, adaption of fertilisation strategies may interfere with local conditions, e.g. difficulty of access to fields with heavy machinery at earlier times in the vegetation period or with national regulations for fertilisation for agriculture that prohibit fertiliser application during specific times during the year (e.g. Nitrate Vulnerable Zone regulations). This may hamper the use of fertilisers like clover grass silage that are otherwise very suitable for horticultural and arable cropping systems (with low contamination risks, additional rotational benefits, additional N-fixation, low cost). In addition, on-farm grown fertilisers (legume-based, plant liquid extracts) may increase the resilience of organic farming systems as the dependence on external fertilisers is reduced. However, it has to be considered for all on-farm produced fertilisers, that in the long run nutrient losses resulting from the sale of produce have to be compensated for by external fertilisers, as only N in case of legumes can be introduced into the cropping system via N fixation on farm level, while all other nutrients, in particular P and K, are only reallocated within the farm.

In particular, fertilisers in the category URBAN show, on the one hand, very good properties for fertilisation due to their high NH_4-N contents but, on the other hand, such fertilisers may lead to specific contamination risks. For instance, plastic residues are found in these fertilisers. National regulations (e.g. RAL-Gütezeichen in Germany) exists that limit the content of unwanted particles, but even if the biogas digestates from source separated organic household waste are below the threshold values, farmers often perceive the macro plastic contamination as too high. In addition, micro plastic is also present in the fertiliser to an unknown amount, as no standard methods for micro plastic determination exist to date. For heavy metals, the digestates used in the current research work showed lower contents of Zn and Cu than frequently found in conventional pig slurry (cf. D 5.7. Technical Report on WP 5.4 SOIL). In general, biogas digestates from source separated organic household waste may contain pesticides, organic pollutants and pathogens, however, the risk for the environment is considered to be low (Govasmark et al. 2011; Möller and Schultheiß 2014). The current Commission Implementing Regulation (EU) 2021/1165 amending the new EU-Regulation on Organic Food and Farming 2018/848 permits the use of composted or fermented mixtures of household waste with certain restrictions (threshold values for heavy metals, only for closed systems monitored by the member state). However, as biogas digestates from source separated organic household wastes are less frequently used than composts, it is recommended that farmers contact their organic control body prior to use. RESID materials like algae fibre can contain naturally high amounts of unwanted compounds like As, but we could not find any uptake by plants fertilised with these materials. To minimise contamination risks threshold values for As contents should be defined before algae fibres are permitted as a fertiliser in organic farming.

All base fertilisers, even those of organic origin, contain contaminants at certain levels and it is not possible to completely exclude such contamination. The organic sector therefore needs to find ways to deal with recycling materials as recycling of nutrients is a core idea in organic farming but trade-offs with environmental aspects and food safety inevitably exist. Plant-based fertilisers (legume-based or leaf extracts) contain little contamination (Table 7), but show other trade-offs concerning nutrient availability or workload for their preparation.

Today, a large variety of residues from food industries and sustainable wild collection/ fisheries is already used as fertilisers in organic farming, but a considerable potential of residual materials remains untapped. Before such products can be used in organic farming, technical issues that prevent the application as fertiliser often have to be solved. The example of tofu whey shows some of the potential issues: the residual material is quite heterogeneous resulting in varying nutrient contents in different batches, which limits its suitability as a fertiliser. In addition, further technological treatments are needed in order to reduce the water content to make shipping of the tofu whey concentrate feasible for the use in organic agriculture. Besides technological issues organic certification itself creates an obstacle for the use of residual materials. As only those materials that are listed in Commission Implementing Regulation (EU) 2021/1165 can be used as fertilisers and soil amendments in organic farming. This results in difficulties and time-consuming processes with control bodies when farmers want to use such products as we experienced when searching for permission to use the tofu whey in our field trial. Therefore, many of these residual materials may have to remain unused and their nutrients are disposed of, as they cannot be applied as fertilisers in organic agriculture. They could be used in conventional agriculture, of course, replacing fossil-fuel derived synthetic fertiliser inputs, however conventional farming is usually not interested in these fertilisers as they are more expensive (at least currently) compared to fossil-fuel derived fertilisers. In addition, their nutrient availability is very different to synthetic fertilisers.

Finally yet importantly, the costs of the alternative fertilisers are crucial for acceptance by farmers. Now, biogas digestates either from source separated household waste or from on-farm residues are cheap and easily available, unless transporting distance and thereby transport cost become too high. Residual materials like organic fish pond sediments and organic tofu whey are available for free or at very low cost, but their use is only feasible close to the production site as transport costs in both cases are very high and nutrient concentration in the currently available residual material is low (Table 7, for more details see D. 5.7). For plant-based fertilisers like clover-grass silage, legume meals and plant extracts from stinging nettle and comfrey the costs per kg N depend very much on the mechanisation of the production process on-farm, on the local labour costs and on the mechanisation of the fertilisation itself, therefore a conclusive assessment based on the outcomes of our trials is difficult. Clover pellets are currently rarely used in commercial farming as the price of approximately 20€ per kg N is very expensive when compared to horn grit or other fertilisers that are used in practice. However, we assume a drop in prices as soon as the product is well established on the market (at the moment mostly for home gardeners) and largescale production facilities exist.

Besides the issues mentioned above, further challenges and potentials concerning the sustainability of the alternative fertilisers exists, e.g. concerning energy use. As drying and pelleting of clover grass biomass requires large amounts of energy, the question arises whether these fertilisers are acceptable from a sustainability perspective. Therefore, transparency on the source of energy (renewable or fossil) used for the production process is needed to assess the environmental impact. On-farm produced legume-based fertilisers offer, in contrast, many benefits including an enhancement of N fixation on farm and additional biomass production on the legume field that may lead to improved soil properties (soil structure, soil organic matter content).

Whether one of the alternative fertilisers tested in Task 5.4 is suitable or not for a particular farm to phase out contentious fertiliser largely depends on the regional context and the farming system itself including the priorities of the farmer but also of the regional/national organic sector. This becomes evident if trade-offs of the alternative fertilisers are considered but also if fertilisation strategies need to be adapted.

Table 7: Summary of alternative fertilisers tested in work package 5.4.

Fertiliser type	Fertiliser	Production type	Fertilisation effect	Contamination risk	Application	Availability	Costs
VEGAN	Clover-grass silage	Vegetable	medium-low	very low	machinery necessary	easy	low
	Clover pellets	Vegetable	High	very low	easy	easy	high
	Bean powder	Greenhouse	High	very low	easy	easy	high
	Comfrey liquid	Greenhouse	Medium	very low	easy	easy but labour intensive	medium
	Nettle liquid	Greenhouse	Medium	very low	easy	easy but labour intensive	medium
URBAN	Biogas digestate (source separated household waste)	Vegetable	very high	high* (depending on source)	easy	depending on location	low
	Biogas digestate (source separated household waste)	Arable	very high	high* (depending on source)	easy	depending on location	low
RESID	Biogas digestate (clover-grass & pig slurry)	Vegetable	very high	high* (depending on source)	easy	depending on location	low
	Tofu whey	Vegetable	medium-high	low	machinery necessary	depending on location	low-medium
	Algae fibre	Arable	Low immediate but high residual effect	not certified organic	splitting before or during application	only available near production site	free/low cost
	Acid-preserved fish bones	Arable	High immediate but low residual effect	high in P and N, may cause eutrophication	Should be incorporated in soil to avoid consumption by birds and animals	only available near production site	free/low cost
	Compost from organic fish pond sediments	Compost	medium-low	low	easy	depending on location	low

* Main contamination risk for quality controlled biogas digestates: Plastics

5. Conclusions and Outlook

From an overall perspective, the alternative fertilisers tested in Task 5.4 of the Organic-PLUS project can **help to phase out contentious fertilisers** from conventional farming and from conventional food industries as the **yield levels of the harvested crops differ very little from the contentious fertilisers used as controls**.

However, as local differences in availability exist, **fertilisation strategies need to be adapted** for some of the fertilisers and others are not yet permitted for organic farming or technical obstacles prevent their use. If these alternative fertilisers are to be integrated in organic farming, a **regionalisation of fertiliser sourcing** in organic farming is needed that takes the demands of the local organic farming systems into account and integrates locally available residual materials and fertilisers from urban sources. There is **no 'one-size-fits-all' solution** that easily substitutes the currently used contentious inputs. Future fertilisation strategies need to address a **system approach** that may need to extend system borders to neighbouring farms and food industries and may include producer-consumer relationships on an **urban-rural territorial scale**.

In future, the organic sector needs to **discuss trade-offs** between the dependency on conventional farming systems, potential contamination risks of fertilisers from sustainable wild collection / fisheries and of fertilisers from urban sources. In addition, **administrative processes in certification for the recognition of fertilisers** need to be changed to permit a faster use of alternative fertilisers in particular **from (organic) food production**.

Fertiliser sources of all three categories addressed in task 5.4 need to be mobilised to source sufficient nutrients for organic farming to reach the **25% certified organic land** share goal stated in the **Farm-to-Fork-Strategy of the Green Deal**, or the 30% organic land share adopted by some EU member states.

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