



# D2.3 Field trial report on agronomic efficiency of Recycled Nutrient Fertilizers

*Piloting field-scale applications of recycled nutrients*

**April, 2026**

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**This #MadeWithInterreg project helps drive the transition to a green and resilient Baltic Sea region and is part of the EU-funded Interreg Baltic Sea Region (BSR) core project #C049, titled CiNURGi, under the 2021-2027 PROGRAMME, Priority 3: Climate-Neutral Societies, Objective 3.1: Circular Economy.**

**Organisations from the following countries cooperate together to make that happen: Sweden (LP), Denmark, Estonia, Finland, Germany, Latvia, Lithuania and Poland.**

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## Foreword

CiNURGi (Circular Nutrients for a Sustainable Baltic Sea Region) is an Interreg BSR Core Project dedicated to advancing the circular economy for nutrients within the Baltic Sea Region. By enhancing infrastructure, technology, and policy, the project seeks to improve nutrient recovery from biomass and resource streams originating from agricultural, municipal, and industrial sources. This endeavor aligns with several regional and European strategies, including the HELCOM Baltic Sea Regional Nutrient Recycling Strategy, the EU's Circular Economy Action Plan under the Green Deal, and the Integrated Nutrient Management Action Plan of the Farm to Fork Strategy. The CiNURGi is ongoing from November 2023 to October 2027.

This task A2.3 report focuses on piloting the field-scale use of Recycled Nutrient Fertilizers (RNFs) to demonstrate their effects under real farming conditions. The findings and activities detailed herein contribute directly to CiNURGi's overarching goals by providing additional evidence on the agronomic performance of RNFs and by increasing awareness of their use as effective fertilizer products.

We acknowledge the collaborative efforts of our consortium, comprising 24 partners and 13 associated organisations from Denmark, Estonia, Finland, Germany, Poland, Latvia, Lithuania, and Sweden. Their dedication and expertise are instrumental in driving the project's success.

For more information about CiNURGi and its initiatives, please visit our project homepage <https://interreg-baltic.eu/project/cinurgi/>

April 2026

Erik Sindhøj & Cheryl Cordeiro, CiNURGi Project Coordinators

RISE – Research Institutes of Sweden

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## List of abbreviations

|   |   |
|---|---|
| AL  | Ammonium Lactate  |
| AN  | Ammonium Nitrate  |
| ANOVA   | Analysis of Variance  |
| ANR   | Apparent Nitrogen Recovery  |
| APR   | Apparent Phosphorus Recovery                                      |
| ASL   | Ammonium Sulphate Liquid/Solution                                 |
| BSR   | Baltic Sea Region   |
| C   | Carbon  |
| CAN   | Calcium Ammonium Nitrate  |
| CAP   | Common Agricultural Policy  |
| CiNURGi   | Circular Nutrients for a Sustainable Baltic Sea Region project    |
| Corg  | Organic Carbon  |
| DHA   | Soil Dehydrogenase Activity                                       |
| DM  | Dry Matter  |
| ES  | Experimental Station  |
| EU  | European Union  |
| FA  | Fulvic Acids  |
| GAEC  | Good Agricultural and Environmental Conditions                    |
| HA  | Humic Acids   |
| HELCOM  | Helsinki Commission   |
| HM  | Hair Meal Pellets   |
| HSD   | Honest Significant Difference                                     |
| HUM   | Humins  |
| IUNG  | Institute of Soil Science and Plant Cultivation in Puławy, Poland |
| JKI   | Julius Kühn-Institute in Braunschweig, Germany                    |
| K   | Potassium   |
| K-K <sub>2</sub> O/K <sub>2</sub> O             | Potassium as potassium oxide/Potassium (II) oxide                 |
| MBM   | Meat and Bone Meal  |
| METK  | Centre of Estonian Rural Research and Knowledge                   |
| MF  | Mineral Fertilizer  |
| N   | Nitrogen  |
| NH <sub>4</sub> -N/NH <sub>4</sub> <sup>+</sup> | Ammonium Nitrogen/Ammonium  |
| Nmin  | Mineral Nitrogen  |
| NO <sub>3</sub> -N/NO <sub>3</sub> <sup>-</sup> | Nitrate Nitrogen/Nitrate  |
| NU  | Nitrogen Uptake   |

|                                 |   |
|---------------------------------|---|
| P                               | Phosphorus                                  |
| PD                              | Pelletized Digestate                        |
| P-P <sub>2</sub> O <sub>5</sub> | Phosphorus as phosphorus (V) oxide          |
| PU                              | Phosphorus Uptake                           |
| RISE                            | Research Institutes of Sweden               |
| RNF                             | Recycled Nutrient Fertilisers               |
| S                               | Sulphur                                     |
| SD                              | Standard Deviation                          |
| SLU                             | Swedish University of Agricultural Sciences |
| SPAD                            | Soil Plant Analysis Development             |
| S-SO <sub>3</sub>               | Sulphur as Sulphur (VI) oxide               |
| S-SO <sub>4</sub>               | Sulphate sulphur                            |
| ST                              | Struvite                                    |
| SW                              | Sheep Wool pellets                          |
| TSF                             | Triple Super Phosphate                      |
| USDA                            | United States Department of Agriculture     |

## Executive Summary

The CiNURGi project's field trials conducted in Estonia, Poland, Sweden, and Germany assessed the agronomic performance of a diverse range of Recycled Nutrient Fertilizers (RNFs). These included fertilizer products, such as struvite and ammonium sulphate solution (ASL), which are mineral fertilizers, as well as organic fertilizers, including composts, solid and liquid fraction of digestate, and bio-based pellets. The research specifically featured products developed by project partners or identified within the project's value chains analysis. Alongside these, several market-available and emerging innovative products were assessed to reflect the diversity of solutions currently entering the circular economy.

The trials demonstrated that RNFs effectively support crop growth and nutrient uptake under real-world farming conditions. While conventional mineral fertilizers generally delivered the highest absolute yields, several RNF treatments—particularly those combining recycled phosphorus sources with mineral nitrogen—achieved comparable results. Beyond yield, organic RNFs provided supplementary benefits, including improved soil structure, increased organic matter input, and enhanced long-term nutrient retention. These outcomes confirm that RNFs are not only viable alternatives for replacing part of the nutrients supplied by mineral fertilizers but can also be successfully integrated into sustainable, large-scale fertilization strategies.

Comprehensive soil analyses revealed that the application of RNFs had no adverse effects on soil pH, macronutrient status, or organic carbon levels. In many instances, organic RNFs enhanced biological activity and improved key soil health indicators. Although specific crop responses varied with local climatic and pedological conditions, the collective evidence from all participating countries identifies RNFs as fertilizer products that can reduce reliance on conventional fertilizers while fulfilling nutrient recycling objectives.

By providing robust, field-based evidence, the CiNURGi project strengthens the regional capacity to adopt circular nutrient solutions. These findings directly support the Interreg BSR mission of fostering a resilient, resource-efficient, and climate-neutral Baltic Sea Region.

Keywords: Field trial evaluation of recycled P- and N-rich fertilizers; Recycled Nutrient Fertilizers (RNFs), phosphorus uptake, nitrogen uptake, fertilizer agronomic efficiency

# 1. Introduction

The transformation of agriculture in the Baltic Sea region toward the greatest possible use of circular economy principles has become one of the key environmental and strategic challenges for the entire macro-region. At the heart of this transition lies the need for effective recovery of nutrients from raw and waste materials and to reuse them in plant production. Although nutrient-recovery technologies are developing rapidly, it is the acceptance of the final products, Recycled Nutrient Fertilizers (RNF), that ultimately determines whether nutrient cycles can be truly closed. A persistent trust gap remains: many farmers, accustomed to the stability and predictability of mineral fertilizers, perceive RNF as a less reliable solution that may require additional knowledge or pose risks to crop performance. The CiNURGi project addresses this challenge by combining demonstration activities, advisory support, and education to show that RNF can become a fully integrated component of modern fertilization systems.

The efforts undertaken within the project align with the broader framework of regional policies, particularly the Baltic Sea Regional Nutrient Recycling Strategy and the updated Baltic Sea Action Plan (BSAP 2021). These documents set an ambitious objective: by 2027, the Baltic Sea region should become a reference area for nutrient recycling, which is crucial for mitigating eutrophication — one of the most severe threats to the marine ecosystem. Achieving this goal requires both technological solutions and practical evidence that RNF can effectively replace part of the nutrients supplied through mineral fertilizers without compromising crop productivity. Task A2.3 of the CiNURGi project responds to these needs by providing data from field and demonstration trials conducted under real farming conditions.

This report presents the results of the agronomic assessment of selected RNF products, including struvite, ammonium sulphate solution (ASL), composts, solid and liquid fraction of digestate, and bio-based pellets, evaluated for their effectiveness in supplying plant nutrients and supporting crop yield. At the same time, the assessment considered their influence on key soil properties, such as macronutrient cycling, organic matter dynamics, and soil pH, which collectively determine long-term soil fertility and the stability of crop production.

The agronomic evaluation presented in this report was carried out by four research institutions representing different parts of the Baltic Sea Region: the Centre of Estonian Rural Research and Knowledge (METK), the Julius Kühn-Institute (JKI) in Germany, the Swedish University of Agricultural Sciences (SLU), and the Institute of Soil Science and Plant Cultivation (IUNG) in Poland (Fig. 1). Their coordinated efforts enabled the assessment of a broad portfolio of RNF products, including struvite produced by SF-SoepenberG GmbH (project partner), the Planteo and Gellebo Götting pellets featured on the CiNURGi value chain longlist, as well as ammonium sulphate solution (ASL), digestates, composts, biochars, pellets and other innovative fertilizers emerging on the European market. This diversity ensured that the trials reflected both established and next-generation nutrient-recycling technologies, providing a robust evidence base for evaluating their agronomic performance under real farming conditions.

The report also describes the dissemination, demonstration, and educational activities conducted by the project partners as part of their field trials, providing stakeholders with reliable data that can support decision-making relevant to agricultural practice. By demonstrating that RNF can replace part of the nutrients supplied through mineral fertilizers and form an important component of a sustainable fertilization plan, the CiNURGi project contributes to building a more resilient and resource-efficient agricultural sector. Nutrient recycling is no longer just an environmental concept;

it is becoming a viable alternative to conventional fertilizers, which, with appropriate support, could gradually become a part of agricultural practice in the Baltic Sea region.

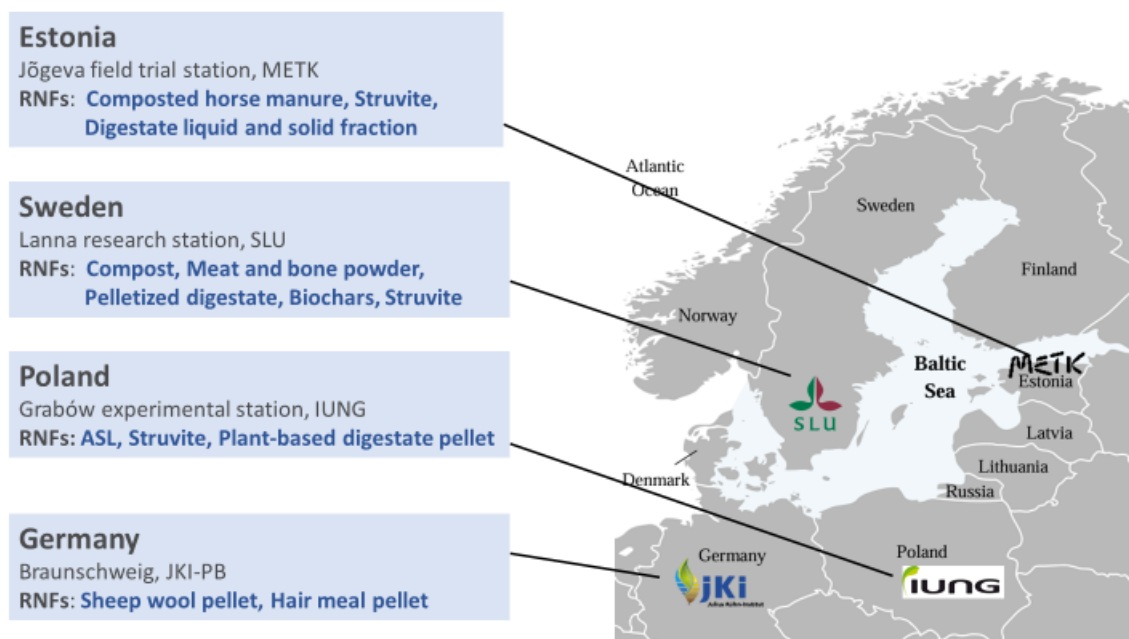


Figure 1. Field-based agronomic assessment of recycled nutrient fertilizers produced in the Baltic Sea Region

## 2. Field trials general methodology

### 2.1. Objective

The primary objective of these field trials is to evaluate the agronomic efficiency of Recycled Nutrient Fertilisers (RNF) in comparison to standard mineral or organic fertilization under real agricultural conditions. These experiments aim to demonstrate the potential for replacing a portion of conventional mineral fertilizers with RNF products in crop production. The research will allow for a reliable assessment of the impact of RNFs on crop yield, nutrient uptake, and overall plant growth and development. Furthermore, the field results will serve to visually present the effects of these products and promote them as high-value fertilizing alternatives. An essential component of the study will also involve analysing the impact of RNFs on selected soil properties, such as organic matter content, microelements, and available forms of nitrogen, phosphorus, and potassium.

### 2.2. General characteristics of the trial

All trials were organised according to the following set of recommendations to ensure a consistent approach across sites. The experiments are conducted over two consecutive growing seasons. It is permissible to test a single fertilizer over two years to ensure higher reliability of results or to evaluate its performance across different plant species. A one-year trial is recommended only if it facilitates the testing of a larger number of fertilizers, particularly those developed within the CiNURGi project. Plant species and varieties are selected according to local environmental conditions and the existing research expertise of the project partners. All agricultural management needs to follow Good Agricultural Practices (GAP) largely enforced through Common Agricultural Policy (CAP) conditionality and Good Agricultural and Environmental Conditions (GAEC) standards, including proper soil preparation and plant protection. Fertilization levels are tailored to the nutritional requirements of the crops, ensuring that macronutrient rates remain identical across comparable

variants, with the only difference being the source of the fertilizer. The plot size must be sufficient to ensure statistically reliable results, and it is suggested that trials be located on soils with low nutrient availability to fully demonstrate the efficiency of the fertilization.

### 2.3. Design of the trial

The field study should follow a one-factor design, involving at least one crop species and testing a minimum of two RNF fertilizers. Priority should be given to products manufactured by CiNURGi project partners, although fertilizers available on the local or EU market may be used, provided they meet relevant quality and legal requirements.

Treatment Groups:

‘Mineral’ RNFs: (e.g., struvite, ammonium sulphate solution – ASL). The control treatment is standard NPK mineral fertilization.

‘Organic’ RNFs: (e.g., solid fraction of digestate, compost, biochars). The control treatment is an unfertilized plot and/or a plot treated with traditional manure.

All fertilizers must be applied using the same method, involving uniform spreading and incorporation into the topsoil to a depth of at least 10 cm. The trial layout must allow for detailed statistical analysis. It is also recommended to include additional rates of mineral nitrogen to precisely determine the nitrogen fertilizer replacement value of the RNF products. All trials must be carried out with at least three replications.

### 2.4. Analyses and sampling

The scope of analysis includes both mandatory and extended data, which partners may implement voluntarily based on their available resources.

Soil samples should be collected twice per season: once before establishing the experiment for field reconnaissance and again after harvest from each experimental treatment’s plot. Basic soil analysis should include pH, organic carbon content, and primary macronutrients using analytical methods commonly accepted in the partner’s country. Samples should be taken from a depth of 0–30 cm, and for mineral nitrogen analysis, they must be transported in refrigerated conditions to prevent uncontrolled mineralization. The extended scope may include monitoring deeper soil profiles and analysing microelements. Plant samples will be collected during key developmental stages to evaluate biomass and at harvest to determine yield and nutrient content (N, P, K). This allows the calculation of both nitrogen uptake (N uptake) and phosphorus uptake (P uptake) based on nutrient concentrations and harvested biomass. The extended analysis scope may also cover SPAD measurements, secondary macronutrients, and total nutrient uptake with the yield.

### 2.5. Field trial report

Each partner prepared a separate chapter for a joint final report based on their obtained results. The reports include a detailed research methodology, a description of weather conditions such as temperature and precipitation, and a presentation of results showing the impact of RNF fertilizers on crop yields and soil properties.

### 2.6. Dissemination & synergy

Partners conducting the trials are required to share knowledge regarding the use of RNFs with key stakeholders, including farmers, agricultural advisors, and students. These activities should include workshops, field visits, and training sessions organised during critical vegetation stages to allow for visual assessment of the results. It is also essential to collect visual documentation for both scientific and promotional purposes.

## 3. Results

### 3.1. Estonia

#### 3.1.1. Materials and methods

##### Setup of field trial

In Estonia, the field trial with broccoli (*Brassica oleracea* L. convar. botrytis var. italica 'Cezar') took place between June and August in 2024 and 2025. The plot sizes were 1.4 × 7.7 m (10.78 m<sup>2</sup>). The distance between plots is 1.5 m, and the buffer zones around the trial block are 6 m. The trial plots followed a randomized complete block design. Winter wheat was grown on the same plots after broccoli to assess the effect of fertilizers one year after application.

##### Plant sampling and analyses

Broccoli plant samples were collected in the middle of July, and the final harvest was conducted at the beginning of August. To determine the intermediate yield, four plants were taken from each plot (two from each outer row). The middle 4 m of each plot (10 plants per plot) were harvested and analyzed. Fresh aboveground biomass samples (heads, stalks and leaves) were weighed and oven-dried, and the dried biomass samples were weighed again to determine dry matter content. From dried biomass (heads, stalks and leaves), P and N concentrations were determined using an elemental analyzer.

##### Soil sampling and analysis

Soil samples were collected from the layer 0–20 cm of each plot. The soils were sampled before the fertilization to provide a baseline, one month after fertilization to monitor the initial status of the fertilized soil and after broccoli harvesting to investigate the influence caused by fertilization and plant growth. Fresh soil samples were delivered in cool boxes after sampling and stored in the fridge at 4 °C before analysis.

The contents of plant available P, K (Mehlich III (ICP-OES)), pH-KCl (ISO 10390), S (ISO 11048), and Corg (ISO 10694) were determined at all three sampling times. The soil mineral N (NH<sub>4</sub>-N and NO<sub>3</sub>-N (ISO 14256-2)) levels of each treatment were monitored to evaluate the nutrient availability of the fertilizing products during and after the growing season of the broccoli.

The soil microbial activity and community composition (DHA) of each treatment were monitored before fertilization, during the growing season and at harvest to evaluate the impact of fertilizing products on soil health. Soil dehydrogenase activity (DHA) was measured in accordance with Tabatabai (1982). Soil samples (5 g) were incubated at 30°C for 24 h in the presence of an alternative electron acceptor (triphenyl-tetrazolium chloride). The red-tinted product, triphenyl formazan (TPF), was extracted with acetone and measured in a spectrophotometer at 546 nm (BioPhotometer plus).

##### Weather data

The air temperature and precipitation were measured with a temporary weather station located in the same field, about 200 m from the CiNURGi trial blocks, at approximately the same altitude. Other data are measured with the Hobo/Licori weather station RX3000. Air temperature is measured at 2 m above the ground.

##### Statistical Analysis

All data were analysed using one-way ANOVA, followed by Tukey's Honestly Significant Difference (HSD) test with a significance level of  $\alpha = 0.05$ . The normality of residuals was tested using [interreg-baltic.eu/project/cinurgi](https://interreg-baltic.eu/project/cinurgi)

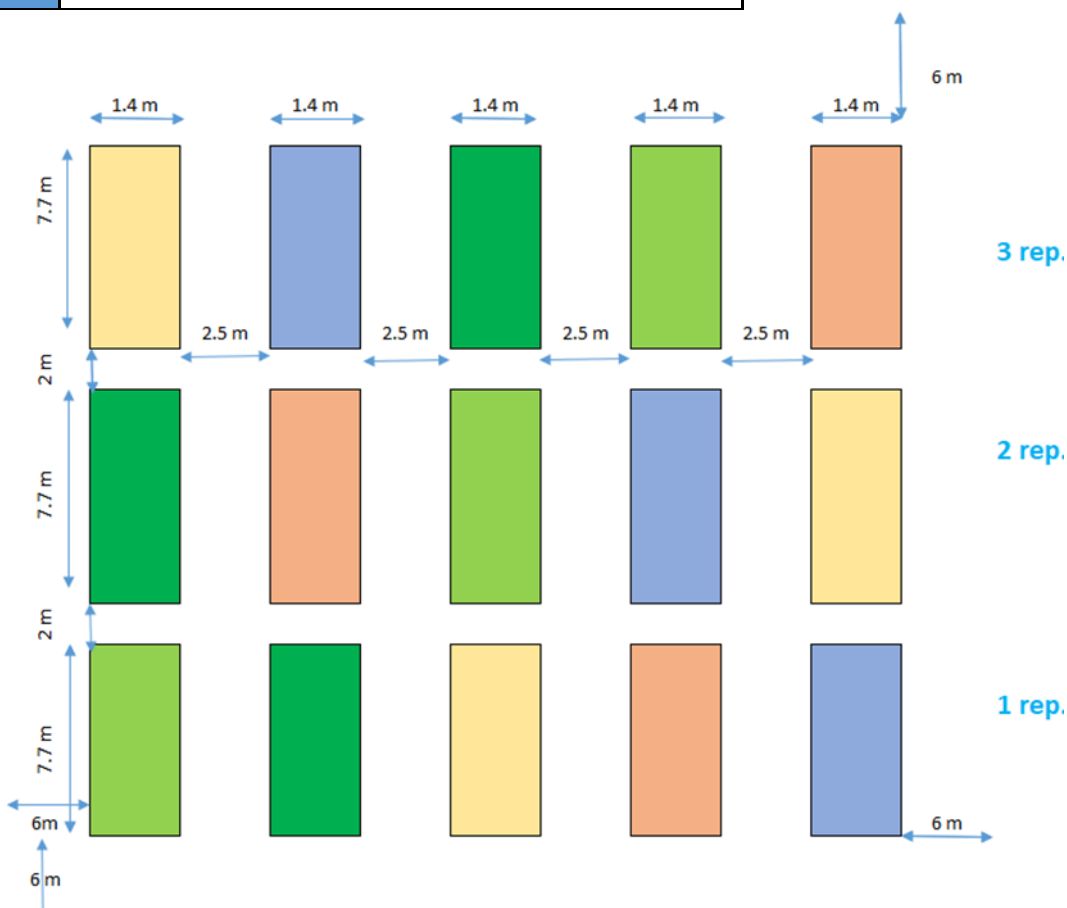
the Shapiro-Wilk test. Analyses were conducted with JMP software, version 11 (SAS Institute Inc., North Carolina, USA).

### 3.1.2. Field trial in season 2024

The field experiment was carried out in Jõgeva, Estonia (58° 46' 35,6118" N, 26° 24' 40,4604" E, altitude 74 m above sea level). The soil at the field trial site is classified as Endogleyic Luvisol (FAO, 2014) with a silty loam texture. Sand 23.40%, silt 63.62%, clay 12.98% (ISO 11277:2020). The field was ploughed in autumn 2023 and harrowed at 10 cm in spring 2024. The field trial with broccoli (*Brassica oleracea* L. convar. botrytis var. italica 'Cezar') took place between June 4 and August 2, 2024.

**Table 1. Field trial treatments.**

|  |  |
|--|--|
|  | 1. Control without fertilizers             |
|  | 2. Mineral fertilizer YaraMila 10-13-25(9) |
|  | 3. Composted horse manure + Struvite + K,  |
|  | 4. Horse manure + AN +Struvite + K,        |
|  | 5. Struvite + AN + KornKali                |



**Figure 2. Trial plots positions in the trial block, plot measures, distances between plots and buffer zones around the trial block. The colour of the plot indicates the fertilisation variant by table 1.**

Each treatment had three replications.

Fertilizer was provided before broccoli planting and incorporated shallowly (14 cm) into the soil. The amount of RNF and mineral fertilizers applied to the treatment was calculated by the NPK content corresponding to a fertilization rate of 120 kg N, 40 kg P and 150 kg K ha<sup>-1</sup> (Table 2).

The broccoli seeds were sown in a planting cassette on May 7, 2024, and the plants were grown in a greenhouse until they were transplanted on June 4 to the field. In each plot, 50 trans-plants were

planted at the 4-leaf stage at a spacing of 0.45×0.45 m in a chess pattern. Plant samples were collected at 5. July 2024, and the final harvesting were done on 2 August 2024.

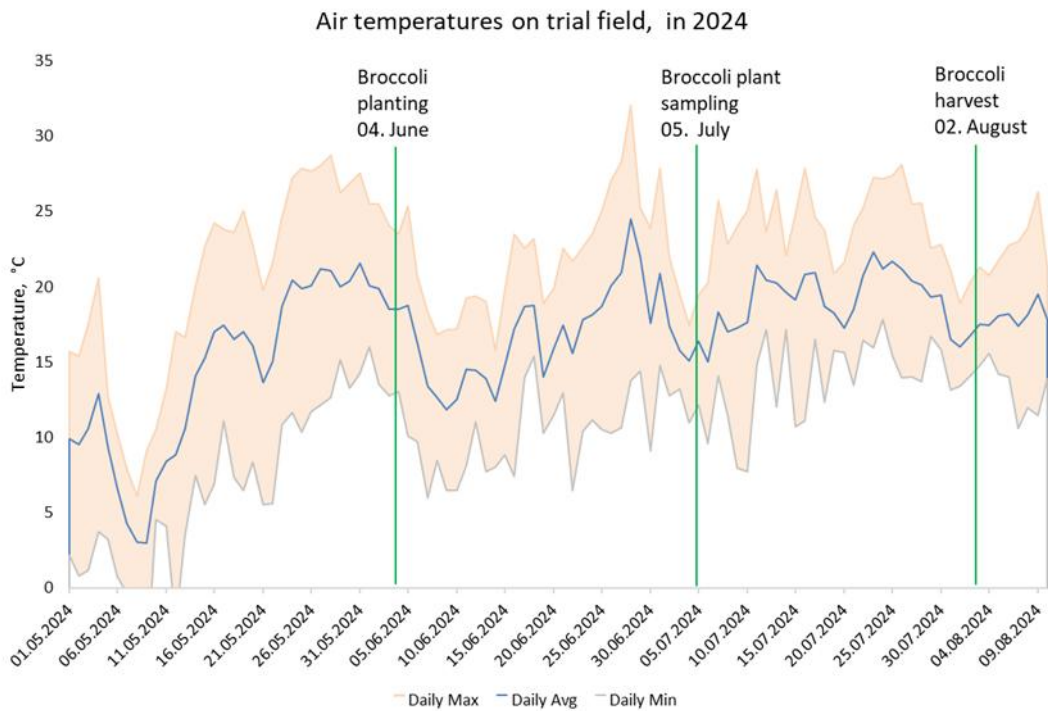
The plots were watered twice, on June 28 and July 19, with a total of 10 l m<sup>-2</sup>. After harvesting, the field trial was ploughed at a depth of 20 cm and harrowed at 10 cm. Winter wheat (*Triticum aestivum* L., Var. Perenaise) was sown on 12 September to evaluate the RNF-s residual effect. Sowing rate was 480 seeds per m<sup>2</sup> (227 kg ha<sup>-1</sup>). The winter wheat seeds were treated with Vibbrance Star (1.5 l t<sup>-1</sup>). No chemical plant protection was applied during the cultivation of broccoli or winter wheat. The plots were managed using hand weeding for weed control, and insect nets were used during the broccoli whole growing period. In addition, sticky traps were installed to monitor and control insect pests. The winter wheat after broccoli was not fertilized.

**Table 2. Nutrient application in different fertilizer treatments**

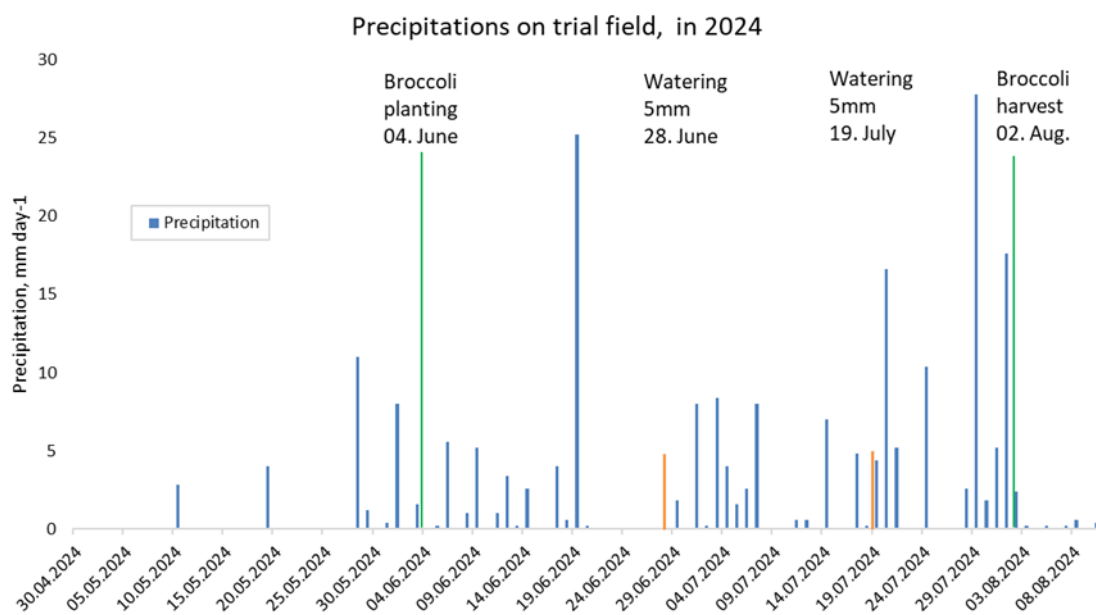
| Treatment                             | Fertilizer   | Nutrients form on fertilizer   | N, kg/ha      | P, Kg/ha     | K, kg/ha      | S, kg/ha     |
|---------------------------------------|--------------|--|---------------|--------------|---------------|--------------|
| Control (unfertilized, CON)           |              |  | 0             | 0            | 0             | 0            |
| Mineral fertilizer NPK (MF)           | 10-13-25(9)  | N-NO <sub>3</sub> ,N-NH <sub>4</sub> ; P-P <sub>2</sub> O <sub>5</sub> ; K-K <sub>2</sub> O; S-SO <sub>3</sub> | 70.57         | 40.00        | 146.44        | 25.41        |
|                                       | AN 34.5      | N-NH <sub>4</sub>  | 49.43         |              |               |              |
|                                       | Korn-Kali    | K-K <sub>2</sub> O, S-SO <sub>3</sub>  |               |              | 3.56          | 0.54         |
|                                       | <b>Total</b> |  | <b>120.00</b> | <b>40.00</b> | <b>150.00</b> | <b>25.94</b> |
| Composted horse manure + Struvite + K | Compost      | Nutrients mostly in organic form   | 68.69         | 17.15        | 79.10         |              |
|                                       | Struvite     | N-NH <sub>4</sub> ; P-P <sub>2</sub> O <sub>5</sub> ; K-K <sub>2</sub> O, S-SO <sub>4</sub>                    | 11.48         | 29.20        | 0.25          | 0.15         |
|                                       | AN 34.5      | N-NH <sub>4</sub>  | 39.84         |              |               |              |
|                                       | Korn-Kali    | K-K <sub>2</sub> O, S-SO <sub>3</sub>  |               |              | 89.31         | 13.45        |
|                                       | <b>Total</b> |  | <b>120.00</b> | <b>46.34</b> | <b>168.66</b> | <b>13.60</b> |
| Horse manure + AN +Struvite + K       | Horse manure | Nutrients mostly in organic form   | 108.59        | 10.98        | 83.05         |              |
|                                       | Struvite     | N-NH <sub>4</sub> ; P-P <sub>2</sub> O <sub>5</sub> ; K-K <sub>2</sub> O, S-SO <sub>4</sub>                    | 11.41         | 29.02        | 0.25          | 0.15         |
|                                       | Korn-Kali    | K-K <sub>2</sub> O, S-SO <sub>3</sub>  |               |              | 66.70         | 10.05        |
|                                       | <b>Total</b> |  | <b>120.00</b> | <b>40.00</b> | <b>150.00</b> | <b>10.19</b> |
| Struvite + AN + K                     | Struvite     | N-NH <sub>4</sub> ; P-P <sub>2</sub> O <sub>5</sub> ; K-K <sub>2</sub> O, S-SO <sub>4</sub>                    | 15.73         | 40.00        | 0.34          |              |
|                                       | AN 34.5      | N-NH <sub>4</sub>  | 104.27        |              |               |              |
|                                       | Korn-Kali    | K-K <sub>2</sub> O, S-SO <sub>3</sub>  |               |              | 149.66        | 22.54        |
|                                       | <b>Total</b> |  | <b>120.00</b> | <b>40.00</b> | <b>150.00</b> | <b>22.54</b> |

### Weather conditions on the CiNURGi trial field, in 2024

In 2024, the air temperatures were between +6 to +32°C during broccoli growth period on field trial, these are lowest minimum and highest maximum (Fig. 3). The average air temperature was +16.8°C during 30 days after planting and plant sampling (4. June -3. July) and +18.9°C during 30 days after that, until harvest (4. July - 2. August). The sum of effective temperatures (daily average degrees over +5°C) was 773°C, and the sum of precipitation was 222 mm from broccoli planting to harvest. The trial block was watered 5 mm twice, because soil sensors indicated low moisture in some periods (Fig 4, orange-coloured columns). The average air temperature +18.5 °C and 0 mm of rain were measured on 4. June 2024, when fertilisers were applied to the trial blocks. The fertilisers were mixed into the soil immediately after application, before noon.



**Figure 3. Air temperatures (daily minimum, average and maximum) by the temporary weather station located in the same field, where the CiNURGi trial block, 2024.**



**Figure 4. Daily precipitation by a temporary weather station located in the same field as the CiNURGi trial block, 2024. Orange columns are amounts and dates of trial block watering.**

### 3.1.3. Results and discussion (2024)

#### Effects of the RNF on broccoli yield, nitrogen and phosphorus uptakes

Tables 3 and 4 present the effects of different fertilizer treatments on broccoli biomass and nutrient uptake at two sampling times. At mid-season (5 July 2024), total aboveground dry biomass and nitrogen (N) and phosphorus (P) uptake were measured to evaluate early growth and nutrient acquisition. At harvest (2 August 2024), head dry biomass was recorded alongside nutrient uptake to assess final yield and nutrient accumulation.

**Table 3. Dry yield of broccoli aboveground biomass (stalks and leaves), N and P concentrations in aboveground biomass under different fertilizer treatments (mean  $\pm$  SD, n = 3), samples collected on 5 July 2024.**

| Treatment                             | Total aboveground biomass      | N uptake                      | P uptake                     |
|---------------------------------------|--------------------------------|-------------------------------|------------------------------|
|                                       | DM kg ha <sup>-1</sup>         | kg ha <sup>-1</sup>           | kg ha <sup>-1</sup>          |
| CON                                   | 1044.3 $\pm$ 100 <sup>b</sup>  | 46.4 $\pm$ 7.1 <sup>b</sup>   | 4.13 $\pm$ 0.6 <sup>b</sup>  |
| MF                                    | 1755.6 $\pm$ 332 <sup>a</sup>  | 96.0 $\pm$ 20.3 <sup>a</sup>  | 7.71 $\pm$ 2.0 <sup>a</sup>  |
| Composted horse manure + Struvite + K | 1359.7 $\pm$ 207 <sup>ab</sup> | 67.8 $\pm$ 11.5 <sup>ab</sup> | 5.08 $\pm$ 0.8 <sup>ab</sup> |
| Horse manure + AN +Struvite + K       | 1400.4 $\pm$ 66 <sup>ab</sup>  | 62.2 $\pm$ 5.1 <sup>b</sup>   | 5.48 $\pm$ 0.3 <sup>ab</sup> |
| Struvite + AN + K                     | 1430.1 $\pm$ 138 <sup>ab</sup> | 76.1 $\pm$ 9.5 <sup>ab</sup>  | 5.05 $\pm$ 1.2 <sup>ab</sup> |
| <i>Pr(&gt;F)</i>                      | <i>0.016</i>                   | <i>0.006</i>                  | <i>0.0324</i>                |

Unfertilized (CON), mineral fertilizers (MF) and RNF and mineral fertilizer combinations. Different letters indicate significant differences between treatments at  $p < 0.05$  with the Tukey-Kramer (HSD) test.

**Table 4. Dry yield of broccoli head, N and P concentrations in aboveground biomass under different fertilizer treatments (mean  $\pm$  SD, n = 3), samples collected on 2 August 2024**

| Treatment                             | Yield (heads)                  | N uptake                       | P uptake                     |
|---------------------------------------|--------------------------------|--------------------------------|------------------------------|
|                                       | DM kg ha <sup>-1</sup>         | kg ha <sup>-1</sup>            | kg ha <sup>-1</sup>          |
| CON                                   | 730.9 $\pm$ 323 <sup>c</sup>   | 125.2 $\pm$ 8.2 <sup>c</sup>   | 20.9 $\pm$ 1.6 <sup>b</sup>  |
| MF                                    | 1850.2 $\pm$ 109 <sup>a</sup>  | 218.2 $\pm$ 23.6 <sup>ab</sup> | 29.9 $\pm$ 4.2 <sup>a</sup>  |
| Composted horse manure + Struvite + K | 1023.9 $\pm$ 229 <sup>bc</sup> | 148.8 $\pm$ 23.0 <sup>bc</sup> | 21.0 $\pm$ 1.8 <sup>ab</sup> |
| Horse manure + AN +Struvite + K       | 757.2 $\pm$ 135 <sup>c</sup>   | 130.0 $\pm$ 8.6 <sup>c</sup>   | 19.2 $\pm$ 1.3 <sup>ab</sup> |
| Struvite + AN + K                     | 1511.1 $\pm$ 208 <sup>ab</sup> | 242.3 $\pm$ 48.4 <sup>a</sup>  | 27.7 $\pm$ 5.9 <sup>ab</sup> |
| <i>Pr(&gt;F)</i>                      | <i>0.001</i>                   | <i>0.007</i>                   | <i>0.013</i>                 |

Unfertilized (CON), mineral fertilizers (MF) and RNF and mineral fertilizer combinations. Different letters indicate significant differences between treatments at  $p < 0.05$  with the Tukey-Kramer (HSD) test.

At mid-season, mineral fertilizer (MF) produced the highest total aboveground biomass (1755.6  $\pm$  332 kg ha<sup>-1</sup>), which was about 68% higher than the unfertilized control (CON, 1044.3  $\pm$  100 kg ha<sup>-1</sup>). Other treatments showed intermediate biomass values: Composted horse manure + Struvite + K (1359.7  $\pm$  207 kg ha<sup>-1</sup>), Horse manure + AN + Struvite + K (1400.4  $\pm$  66 kg ha<sup>-1</sup>), and Struvite + AN + K (1430.1  $\pm$  138 kg ha<sup>-1</sup>). Nitrogen uptake followed a similar pattern at mid-season. MF treatment had the highest N uptake (96.0  $\pm$  20.3 kg ha<sup>-1</sup>), significantly exceeding the control (46.4  $\pm$  7.1 kg ha<sup>-1</sup>). Other treatments showed moderate uptake ranging between 62.2  $\pm$  5.1 and 76.1  $\pm$  9.5 kg ha<sup>-1</sup>. Phosphorus uptake at mid-season was also highest under MF (7.71  $\pm$  2.0 kg ha<sup>-1</sup>), nearly double the control (4.13  $\pm$  0.6 kg ha<sup>-1</sup>), with intermediate values in other treatments.

At harvest, the MF treatment resulted in the highest head biomass (1850.2  $\pm$  109 kg ha<sup>-1</sup>), more than double that of the control (730.9  $\pm$  323 kg ha<sup>-1</sup>). Struvite + AN + K also performed well (1511.1  $\pm$  208 kg ha<sup>-1</sup>), while Composted horse manure + Struvite + K (1023.9  $\pm$  229 kg ha<sup>-1</sup>) and Horse manure + AN + Struvite + K (757.2  $\pm$  135 kg ha<sup>-1</sup>) had lower yields. Nitrogen uptake at harvest was highest in the Struvite + AN + K treatment (242.3  $\pm$  48.4 kg ha<sup>-1</sup>), followed by MF (218.2  $\pm$  23.6 kg ha<sup>-1</sup>). Organic manure treatments showed lower N uptake, with Composted horse manure + Struvite + K at 148.8  $\pm$  23.0 kg ha<sup>-1</sup> and Horse manure + AN + Struvite + K at 130.0  $\pm$  8.6 kg ha<sup>-1</sup>. The control had the lowest N uptake (125.2  $\pm$  8.2 kg ha<sup>-1</sup>). Phosphorus uptake patterns at harvest were consistent with biomass and nitrogen uptake trends. MF had the highest P uptake (29.9  $\pm$  4.2 kg ha<sup>-1</sup>), followed closely by Struvite + AN + K (27.7  $\pm$  5.9 kg ha<sup>-1</sup>). Organic manure treatments had lower uptake, like the control.

Statistical analysis indicated significant differences between treatments in biomass and nutrient uptake at both sampling times ( $p < 0.05$ ). Overall, mineral fertilizer (MF) was the most effective in enhancing broccoli biomass production and nutrient uptake throughout the growing season. The Struvite + AN + K treatment also showed strong performance, especially in nitrogen uptake at harvest. Treatments based on horse manure showed limited improvements compared to the control, highlighting the slower nutrient release and lower immediate availability of nutrients in organic fertilizers under the studied conditions.

#### Effects of the RNF on soil physical-chemical and microbiological characteristics in 2024

The analysis of soil chemical properties, dehydrogenase activity (DHA) over three sampling times-before fertilization (June), during broccoli growth (July), and after harvest (August)-reveals interesting trends in how different fertilizer treatments influence nutrient availability. However, it is important to note that significant differences were only observed for nitrate nitrogen ( $\text{NO}_3\text{-N}$ ) (Table 5).

Before fertilization (June): As expected, no significant differences were observed before fertilization across the treatments. Soil parameters were similar across all treatments, indicating that fertilization had not yet occurred, and the initial nutrient levels in the soil were consistent.

During broccoli growth (July): DHA showed an increasing trend across all treatments, suggesting stimulated microbial activity during the growing period; however, these changes were not statistically significant. For example, Horse manure + AN + Struvite + K increased from 7.08 to 10.32  $\mu\text{g g}^{-1} \text{h}^{-1}$ , and Struvite + AN + K from 7.04 to 9.79  $\mu\text{g g}^{-1} \text{h}^{-1}$ .

In contrast, nitrate nitrogen ( $\text{NO}_3^-$ ) showed significant differences between treatments. The Struvite + AN + K treatment had the highest  $\text{NO}_3^-$  concentration (56.67  $\text{mg kg}^{-1}$ ), significantly higher than other treatments, indicating enhanced nitrogen availability that likely supported improved plant growth.

After harvest (August): DHA showed a slight decreasing trend across all treatments compared to July, again without statistical significance (e.g., Struvite + AN + K: 9.79  $\rightarrow$  9.12  $\mu\text{g g}^{-1} \text{h}^{-1}$ ). Similarly, no significant differences were observed between treatments for pH-KCl, P, Corg,  $\text{NO}_3^-$ , or  $\text{NH}_4^+$  at this stage.

Overall, while DHA exhibited only non-significant temporal trends, nitrate nitrogen ( $\text{NO}_3^-$ ) was the only parameter that responded significantly to fertilization, highlighting that nutrient availability responded more strongly to treatments than microbial activity.

**Table 5. Soil chemical characteristics and dehydrogenase activity (DHA) in soil 0-20cm layers at three sampling time under different fertilizer treatments (mean  $\pm$  SD, n=3).**

| Time                          | Treatment                             | pH <sub>KCl</sub> | P                   | Corg              | NO <sub>3</sub> -N   | NH <sub>4</sub> -N  | DHA   |
|-------------------------------|---------------------------------------|-------------------|---------------------|-------------------|----------------------|---------------------|---|
|                               |                                       |                   | mg kg <sup>-1</sup> | %                 | mg kg <sup>-1</sup>  | mg kg <sup>-1</sup> | TPF ( $\mu$ g g <sup>-1</sup> h <sup>-1</sup> ) |
| Before fertilization (June)   | CON                                   | 6.37 <sup>a</sup> | 54.00 <sup>a</sup>  | 2.83 <sup>a</sup> |                      |                     | 7.60 <sup>a</sup>                               |
|                               | MF                                    | 6.47 <sup>a</sup> | 55.67 <sup>a</sup>  | 3.00 <sup>a</sup> |                      |                     | 7.82 <sup>a</sup>                               |
|                               | Composted horse manure + Struvite + K | 6.57 <sup>a</sup> | 49.00 <sup>a</sup>  | 2.73 <sup>a</sup> |                      |                     | 7.28 <sup>a</sup>                               |
|                               | Horse manure + AN + Struvite + K      | 6.57 <sup>a</sup> | 51.67 <sup>a</sup>  | 2.87 <sup>a</sup> |                      |                     | 7.08 <sup>a</sup>                               |
|                               | Struvite + AN + K                     | 6.47 <sup>a</sup> | 49.00 <sup>a</sup>  | 2.93 <sup>a</sup> |                      |                     | 7.04 <sup>a</sup>                               |
| <i>Pr(&gt;F)</i>              |                                       | <i>ns</i>         | <i>ns</i>           | <i>ns</i>         |                      |                     | <i>ns</i>                                       |
| During broccoli growth (July) | CON                                   |                   | 58.33 <sup>a</sup>  |                   | 10.03 <sup>c</sup>   | 1.30 <sup>a</sup>   | 10.05 <sup>a</sup>                              |
|                               | MF                                    |                   | 78.33 <sup>a</sup>  |                   | 37.13 <sup>ab</sup>  | 1.83 <sup>a</sup>   | 10.31 <sup>a</sup>                              |
|                               | Composted horse manure + Struvite + K |                   | 86.00 <sup>a</sup>  |                   | 32.53 <sup>abc</sup> | 6.73 <sup>a</sup>   | 8.91 <sup>a</sup>                               |
|                               | Horse manure + AN + Struvite + K      |                   | 65.33 <sup>a</sup>  |                   | 13.67 <sup>bc</sup>  | 1.27 <sup>a</sup>   | 10.32 <sup>a</sup>                              |
|                               | Struvite + AN + K                     |                   | 105.33 <sup>a</sup> |                   | 56.67 <sup>a</sup>   | 3.70 <sup>a</sup>   | 9.79 <sup>a</sup>                               |
| <i>Pr(&gt;F)</i>              |                                       |                   | <i>ns</i>           |                   | 0.0013               | <i>ns</i>           | <i>ns</i>                                       |
| After harvest (August)        | CON                                   |                   | 54.00 <sup>a</sup>  | 2.87 <sup>a</sup> | 8.20 <sup>a</sup>    | 1.03 <sup>a</sup>   | 8.19 <sup>a</sup>                               |
|                               | MF                                    |                   | 58.67 <sup>a</sup>  | 2.97 <sup>a</sup> | 8.43 <sup>a</sup>    | 0.80 <sup>a</sup>   | 9.16 <sup>a</sup>                               |
|                               | Composted horse manure + Struvite + K |                   | 61.00 <sup>a</sup>  | 2.87 <sup>a</sup> | 8.90 <sup>a</sup>    | 0.63 <sup>a</sup>   | 8.70 <sup>a</sup>                               |
|                               | Horse manure + AN + Struvite + K      |                   | 62.33 <sup>a</sup>  | 3.00 <sup>a</sup> | 10.13 <sup>a</sup>   | 1.47 <sup>a</sup>   | 8.94 <sup>a</sup>                               |
|                               | Struvite + AN + K                     |                   | 64.00 <sup>a</sup>  | 2.90 <sup>a</sup> | 10.87 <sup>a</sup>   | 1.00 <sup>a</sup>   | 9.12 <sup>a</sup>                               |
| <i>Pr(&gt;F)</i>              |                                       |                   | <i>ns</i>           | <i>ns</i>         | <i>ns</i>            | <i>ns</i>           | <i>ns</i>                                       |

Unfertilized (CON), mineral fertilizers (MF) and RNF and mineral fertilizer combinations. Different letters indicate significant differences between treatments at  $p < 0.05$  with the Tukey-Kramer (HSD) test.

ns – not significant

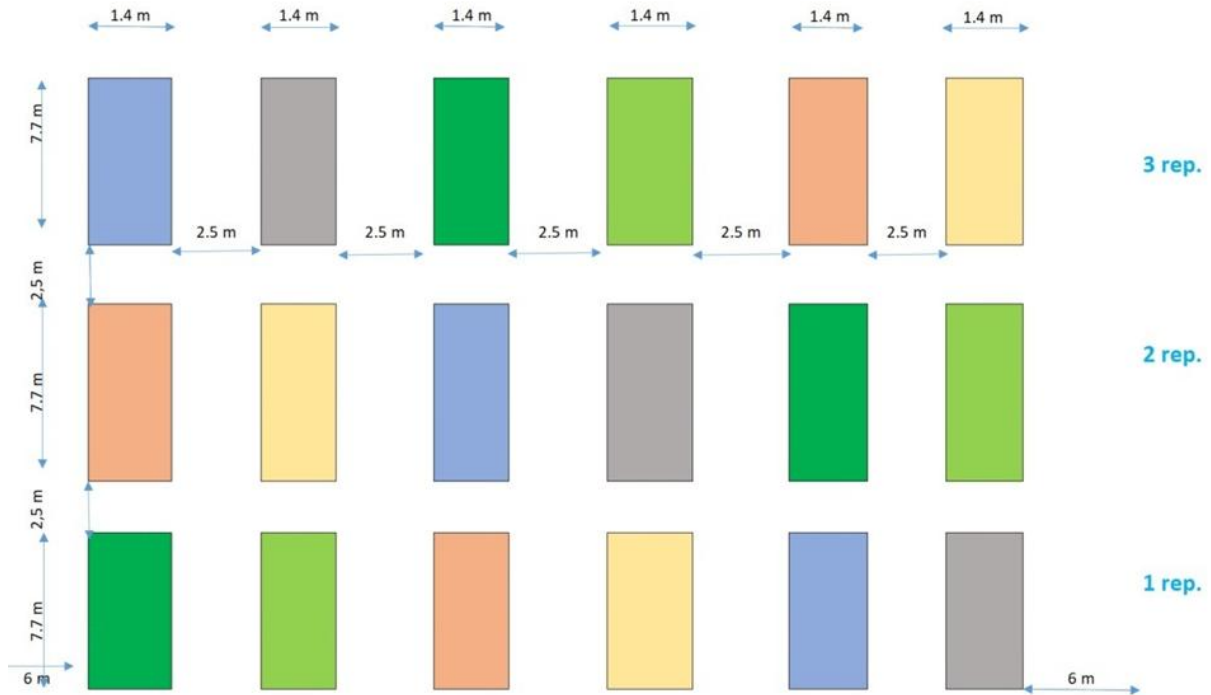
### 3.1.4. Field trial in season 2025

The field experiment was carried out in Jõgeva, Estonia (58°46'36,7" N, 26°24'40,0" E, altitude 74 m above sea level). The soil at the field trial site is classified as Endogleyic Luvisol (FAO, 2014) with a silty loam texture. Sand 22.61%, silt 69.15%, clay 8.24% (ISO 11277:2020).

The field was ploughed in autumn 2024 and disc-harrowed to a depth of 10 cm in spring 2025. Broccoli (*Brassica oleracea* L. convar. botrytis var. italica 'Cezar') seeds were sown in planting cassettes on 5. In May 2025, the seedlings were grown in a greenhouse until transplanting. Transplanting to the field took place on 10. June 2025. In each plot, 50 transplants at the four-leaf stage were planted at a spacing of 0.45  $\times$  0.45 m in a chess pattern. Broccoli was harvested on 5 August 2025.

**Table 6. Field trial treatments.**

|  |   |
|--|---|
|  | 1. Control without fertilizers  |
|  | 2. Mineral fertilizer YaraMila 10-13-25(9)  |
|  | 3. Digestate liquid fraction (+ struvite + KornKali)                                  |
|  | 4. Digestate solid fraction (+ struvite + KornKali)                                   |
|  | 5. Struvite + AN + KornKali   |
|  | 6. Digestate liquid fraction (+ struvite + KornKali) + H <sub>2</sub> SO <sub>4</sub> |



**Figure 5. Trial plots positions in the trial block, plot measures, distances between plots and buffer zones around the trial block. The colour of the plot indicates the fertilisation variant by table 6.**

Each treatment was established in 3 replications.

Fertilizers (Table 7) were applied before broccoli transplanting and incorporated shallowly into the soil to a depth of approximately 14 cm. The application rates of RNF and mineral fertilizers were calculated based on their N, P, and K contents, corresponding to a target fertilization rate of 120 kg N, 40 kg P, and 150 kg K ha<sup>-1</sup> (Table 7).

**Table 7. Nutrient application in different fertilizer treatments, in the 2025 trial**

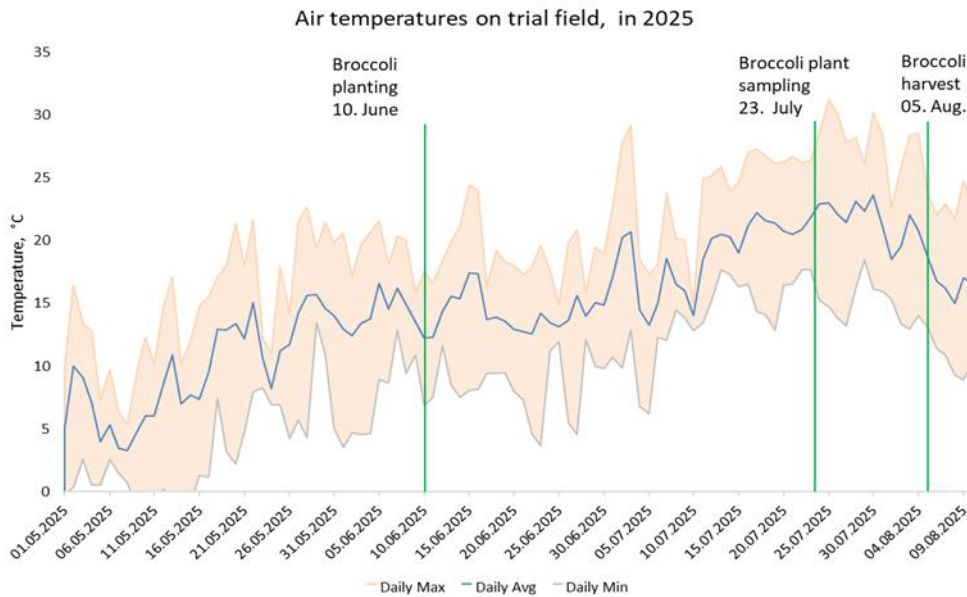
| Treatment   | Fertilizer   | Nutrients form on fertilizer  | N,<br>kg/ha   | P,<br>Kg/ha  | K,<br>kg/ha   | S,<br>kg/ha  |
|---|--------------|---|---------------|--------------|---------------|--------------|
| Control (unfertilized, CON)   | -            | -   | -             | -            | -             | -            |
| Mineral fertilizer NPK (MF)   | 10-13-25(9)  | N-NO <sub>3</sub> , N-NH <sub>4</sub> ; P-P <sub>2</sub> O <sub>5</sub> ; K-K <sub>2</sub> O; S-SO <sub>3</sub> | 67.04         | 40.00        | 146.44        | 25.41        |
|   | AN 34.5      | N-NH <sub>4</sub>   | 49.43         |              |               |              |
|   | Korn-Kali    | K-K <sub>2</sub> O, S-SO <sub>3</sub>   |               |              | 3.56          | 0.54         |
|   | <b>Total</b> |   | <b>116.47</b> | <b>40.00</b> | <b>150.00</b> | <b>25.94</b> |
| Digestate liquid fraction (+ struvite + K)                                  | EcoBio       | Nutrients mostly in organic form  | 111.25        | 1.72         | 18.66         | 3.76         |
|   | Struvite     | N-NH <sub>4</sub> ; P-P <sub>2</sub> O <sub>5</sub> ; K-K <sub>2</sub> O, S-SO <sub>4</sub>                     | 15.05         | 38.28        | 0.33          | 0.20         |
|   | Korn-Kali    | K-K <sub>2</sub> O, S-SO <sub>3</sub>   |               |              | 131.01        | 19.73        |
|   | <b>Total</b> |   | <b>126.30</b> | <b>40.00</b> | <b>150.00</b> | <b>23.69</b> |
| Digestate solid fraction (+ struvite + K)                                   | EcoBio       | Nutrients mostly in organic form  | 106.84        | 6.54         | 12.70         | 8.97         |
|   | Struvite     | N-NH <sub>4</sub> ; P-P <sub>2</sub> O <sub>5</sub> ; K-K <sub>2</sub> O, S-SO <sub>4</sub>                     | 13.16         | 33.46        | 0.29          | 0.17         |
|   | Korn-Kali    | K-K <sub>2</sub> O, S-SO <sub>3</sub>   |               |              | 137.02        | 20.64        |
|   | <b>Total</b> |   | <b>120.00</b> | <b>40.00</b> | <b>150.00</b> | <b>22.74</b> |
| Struvite + AN + K   | AN 34.5      | N-NH <sub>4</sub>   | 104.27        |              |               |              |
|   | Struvite     | N-NH <sub>4</sub> ; P-P <sub>2</sub> O <sub>5</sub> ; K-K <sub>2</sub> O, S-SO <sub>4</sub>                     | 15.73         | 40.00        | 0.34          | 0.21         |
|   | Korn-Kali    | K-K <sub>2</sub> O, S-SO <sub>3</sub>   |               |              | 149.66        | 22.54        |
|   | <b>Total</b> |   | <b>120.00</b> | <b>40.00</b> | <b>150.00</b> | <b>22.74</b> |
| Digestate liquid fraction + H <sub>2</sub> SO <sub>4</sub> (+ struvite + K) | EcoBio       | Nutrients mostly in organic form  | 110.86        | 1.72         | 18.66         | 71.75        |
|   | Struvite     | N-NH <sub>4</sub> ; P-P <sub>2</sub> O <sub>5</sub> ; K-K <sub>2</sub> O, S-SO <sub>4</sub>                     | 15.05         | 38.28        | 0.33          | 0.20         |
|   | Korn-Kali    | K-K <sub>2</sub> O, S-SO <sub>3</sub>   |               |              | 131.01        | 19.73        |
|   | <b>Total</b> |   | <b>125.92</b> | <b>40.00</b> | <b>150.00</b> | <b>91.67</b> |

The plots were managed using hand weeding for weed control, and insect nets were used during the broccoli whole growing period. In addition, sticky traps were installed to monitor and control insect pests.

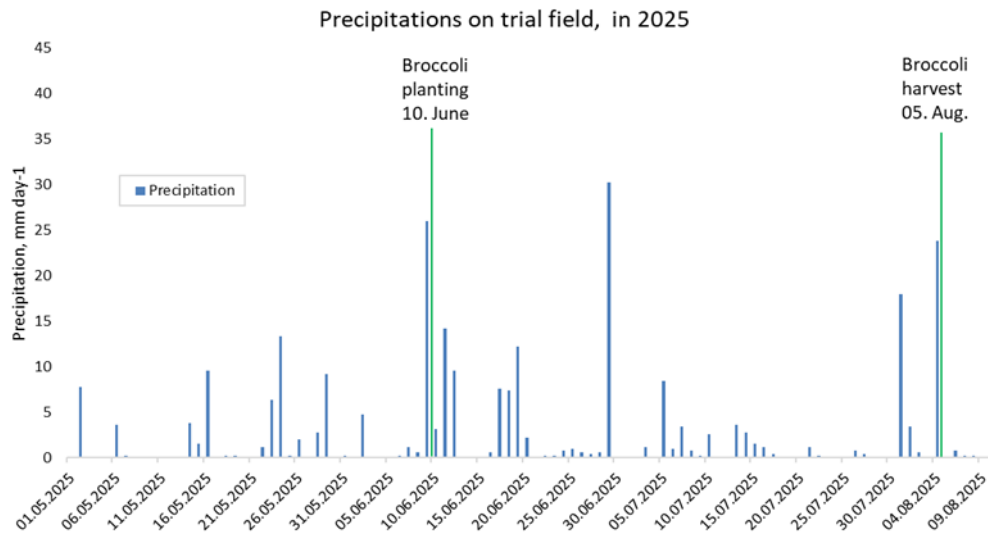
#### Weather conditions on the CiNURGi trial field, in 2025

In 2025, the air temperatures were between +3.6 and +31.2°C during the broccoli growth period on the field trial; these are the lowest minimum and highest maximum (Fig 6). The average air temperature was +15.0°C during 30 days after planting and plant sampling (10 June - 9 July) and +20.8°C during 27 days after that, until harvest (10. July - 5. August). The sum of effective temperatures (degrees over +5°C) was 727°C, and the sum of precipitation was 301 mm from broccoli planting to harvest (Fig. 7). The broccoli plants were not watered during their growth in the field.

The average air temperature +12.3°C and 3.2 mm of rain were measured on 10. June 2025, when fertilisers were applied to the trial blocks. The fertilisers were mixed into the soil immediately after application, before noon.



**Figure 6. Air temperatures (daily minimum, average and maximum) by the temporary weather station located in the same field, where the CiNURGi trial block, 2025.**



**Figure 7. Precipitations by a temporary weather station located in the same field as the CiNURGi trial block, 2025**

During the first half of the broccoli growing season in 2025, the air temperature was lower than in 2024 (Figure 8). However, in the last decades of July 2025, it was higher than in 2024.

In 2025, the air temperatures between the third decade of May and the first decade of July were close to the long term (1991-2000) average (Figure 8). The second and third decades of July were about 4-5 degrees warmer compared to the long-term average.

In 2025, the sum of precipitation in the first decades in June exceeded the long term (1991-2000) sums by 17-19 mm (Figure 9). The first half of July was drier, but the end of July and beginning of august very wet (37-39 mm more than long-term sums).

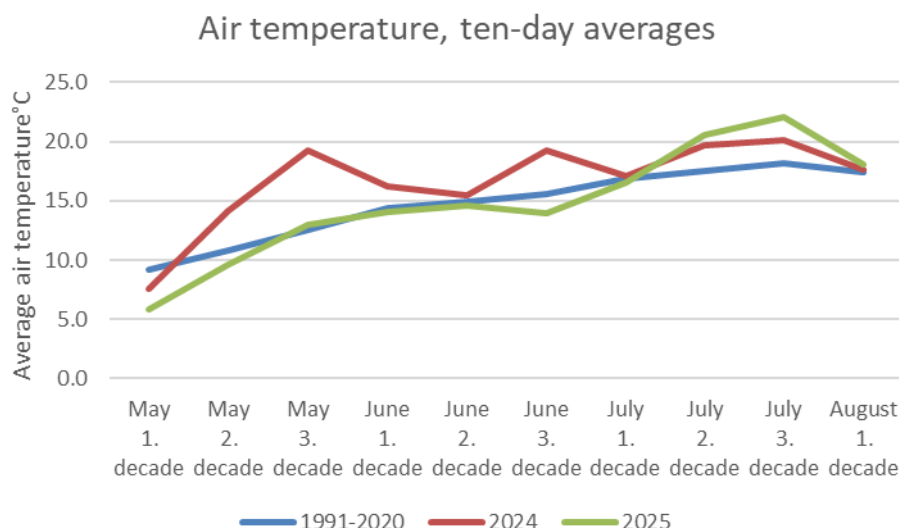


Figure 8. Air temperature ten-day averages in 2024 and 2025, compared to long term (1991-2020) averages

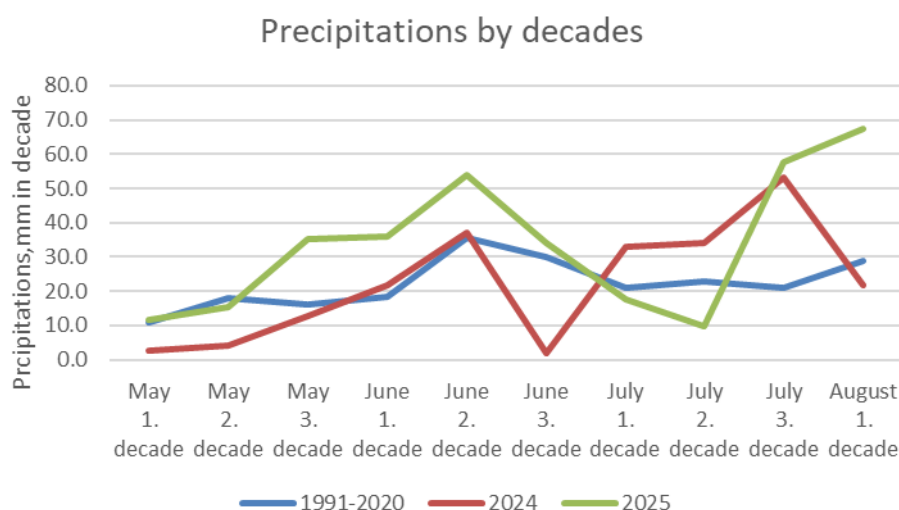


Figure 9. Sums of precipitation by decades in 2024 and 2025, compared to long term (1991-2020) averages

### 3.1.5. Results and discussion (2025)

#### Effects of the RNF on broccoli yield, nitrogen and phosphorus uptakes

At the first sampling on 23 July 2025, fertilizer treatment did not significantly affect aboveground dry matter yield, nitrogen (N) uptake, or phosphorus (P) uptake (Table 8).

Dry matter yield ranging from 1 699.6 kg DM ha<sup>-1</sup> in the control to 2 835.4 kg DM ha<sup>-1</sup> in the mineral fertilizer treatment. The digestate liquid fraction and struvite + AN + K treatments also showed relatively high dry matter yields (2 810.7 and 2798.4 kg DM ha<sup>-1</sup>, respectively), whereas the digestate solid fraction and acidified digestate liquid fraction resulted in intermediate values (2 259.3 and 2 662.6 kg DM ha<sup>-1</sup>, respectively).

Nitrogen uptake ranged from 51.5 kg ha<sup>-1</sup> in the control to about 105 kg ha<sup>-1</sup> in the highest treatments (digestate liquid fraction and struvite + AN + K), with mineral fertilizer showing 97.4 kg ha<sup>-1</sup>. The remaining treatments fell between these values. However, differences among treatments were not statistically significant. Phosphorus uptake followed a similar pattern, increasing from 8.4 kg ha<sup>-1</sup> in the control to a maximum of 14.7 kg ha<sup>-1</sup> in the mineral fertilizer treatment.

At the final harvest on 5 August 2025, the dry yield of broccoli heads and nutrient uptake in aboveground biomass were significantly influenced by fertilizer treatment (Table 9). The control (CON) produced the lowest dry matter yield ( $377.0 \pm 74.4 \text{ kg ha}^{-1}$ ), accompanied by low nitrogen ( $75.7 \pm 7.97 \text{ kg ha}^{-1}$ ) and phosphorus ( $14.0 \pm 2.0 \text{ kg ha}^{-1}$ ) uptake. In contrast, the mineral fertilizer (MF) treatment achieved the highest yield ( $1\,432.3 \pm 65.7 \text{ kg ha}^{-1}$ ) and nutrient accumulation, with nitrogen and phosphorus uptake of  $166.5 \pm 12.74 \text{ kg ha}^{-1}$  and  $26.5 \pm 0.7 \text{ kg ha}^{-1}$ , respectively, demonstrating the strong response of broccoli to readily available nutrients.

Intermediate treatments—including digestate liquid fraction (+ struvite + K), digestate solid fraction (+ struvite + K), Struvite + AN + K, and digestate liquid fraction +  $\text{H}_2\text{SO}_4$  (+ struvite + K)—produced yields ranging from 584.9 to 967.9  $\text{kg ha}^{-1}$ , with corresponding nitrogen uptake of 90.1–142.8  $\text{kg ha}^{-1}$  and phosphorus uptake of 18.7–21.7  $\text{kg ha}^{-1}$ . Although these treatments did not differ significantly from each other, they consistently improved both biomass production and nutrient accumulation compared to the control.

Overall, there was a clear positive correlation between yield and N and P uptake: treatments that provided more available nutrients also resulted in higher biomass production and greater nutrient accumulation in the aboveground tissue. Statistical analysis confirmed significant effects of fertilization on yield ( $Pr > F = 0.029$ ), nitrogen uptake (0.044), and phosphorus uptake (0.05).

**Table 8. Dry yield of broccoli aboveground biomass (stalks and leaves), N and P concentrations in aboveground biomass under different fertilizer treatments (mean  $\pm$  SD, n = 3), samples collected on 23 July 2025.**

| Treatment  | Aboveground biomass              | N uptake                      | P uptake                    |
|--|----------------------------------|-------------------------------|-----------------------------|
|  | DM $\text{kg ha}^{-1}$           | $\text{kg ha}^{-1}$           | $\text{kg ha}^{-1}$         |
| CON  | 1 699.6 $\pm$ 72.3 <sup>a</sup>  | 51.5 $\pm$ 2.7 <sup>a</sup>   | 8.4 $\pm$ 0.6 <sup>a</sup>  |
| MF   | 2 835.4 $\pm$ 207.1 <sup>a</sup> | 97.4 $\pm$ 10.9 <sup>a</sup>  | 14.7 $\pm$ 0.1 <sup>a</sup> |
| Digestate liquid fraction (+ struvite + K)                           | 2 810.7 $\pm$ 668.2 <sup>a</sup> | 105.1 $\pm$ 42.9 <sup>a</sup> | 14.4 $\pm$ 3.1 <sup>a</sup> |
| Digestate solid fraction (+ struvite + K)                            | 2 259.3 $\pm$ 497.1 <sup>a</sup> | 62.0 $\pm$ 19.9 <sup>a</sup>  | 11.8 $\pm$ 2.5 <sup>a</sup> |
| Struvite + AN + K  | 2 798.4 $\pm$ 768.3 <sup>a</sup> | 105.1 $\pm$ 28.8 <sup>a</sup> | 13.8 $\pm$ 3.8 <sup>a</sup> |
| Digestate liquid fraction + $\text{H}_2\text{SO}_4$ (+ struvite + K) | 2 662.6 $\pm$ 807.7 <sup>a</sup> | 82.9 $\pm$ 41.5 <sup>a</sup>  | 14.0 $\pm$ 4.8 <sup>a</sup> |
| <i>Pr(&gt;F)</i>   | <i>ns</i>                        | <i>ns</i>                     | <i>ns</i>                   |

Unfertilized (CON), mineral fertilizers (MF) and RNF and mineral fertilizer combinations. Different letters indicate significant differences between treatments at  $p < 0.05$  with the Tukey-Kramer (HSD) test. ns- not significant

**Table 9. Dry yield of broccoli head, N and P concentrations in aboveground biomass under different fertilizer treatments (mean ± SD, n = 3), samples collected on 5 August 2025**

| Treatment  | Yield (heads)<br>DM kg ha <sup>-1</sup> | N uptake<br>kg ha <sup>-1</sup> | P uptake<br>kg ha <sup>-1</sup> |
|--|---|---------------------------------|---------------------------------|
| CON  | 377.0 ± 74.4 <sup>b</sup>               | 75.7 ± 7.97 <sup>b</sup>        | 14.0 ± 2.0 <sup>b</sup>         |
| MF   | 1 432.3 ± 65.7 <sup>a</sup>             | 166.5 ± 12.74 <sup>a</sup>      | 26.5 ± 0.7 <sup>a</sup>         |
| Digestate liquid fraction<br>(+ struvite + K)                                  | 784.0 ± 367.9 <sup>ab</sup>             | 142.8 ± 46.78 <sup>ab</sup>     | 21.7 ± 5.5 <sup>ab</sup>        |
| Digestate solid fraction<br>(+ struvite + K)                                   | 584.9 ± 227.7 <sup>ab</sup>             | 90.1 ± 11.50 <sup>ab</sup>      | 18.7 ± 3.4 <sup>ab</sup>        |
| Struvite + AN + K  | 967.9 ± 591.8 <sup>ab</sup>             | 132.1 ± 53.66 <sup>ab</sup>     | 21.1 ± 6.3 <sup>ab</sup>        |
| Digestate liquid fraction<br>+ H <sub>2</sub> SO <sub>4</sub> (+ struvite + K) | 731.9 ± 293.5 <sup>ab</sup>             | 106.8 ± 33.05 <sup>ab</sup>     | 21.2 ± 3.9 <sup>ab</sup>        |
| <i>Pr(&gt;F)</i>   | <i>0.029</i>                            | <i>0.044</i>                    | <i>0.05</i>                     |

Unfertilized (CON), mineral fertilizers (MF) and RNF and mineral fertilizer combinations. Different letters indicate significant differences between treatments at  $p < 0.05$  with the Tukey-Kramer (HSD) test. ns- not significant

### Residual effect of previous fertilizer treatments on winter wheat grain yield (growth period Sept 2024 -Aug 2025)

The data presented in Table 10 summarize the residual impacts of the previous fertilizer treatments on winter wheat (sown in autumn 2024 to the plots, where broccoli was harvested in August 2024) grain yield, and phosphorus uptake at the 2025 harvest (6. Aug. 2025).

**Table 10. Residual effects of fertilization on winter wheat (sown in 2024) yield and nutrient uptake by grain at harvest in 2025 (mean ± SD, n = 3).**

| Treatment                             | Yield, (14%<br>moisture)<br>kg ha <sup>-1</sup> | N uptake<br>kg ha <sup>-1</sup> | P uptake<br>kg ha <sup>-1</sup> |
|---------------------------------------|---|---------------------------------|---------------------------------|
| CON                                   | 2245.1±208.9 <sup>a</sup>                       | 36.4±5.3 <sup>a</sup>           | 7.5±0.7 <sup>a</sup>            |
| MF                                    | 2173.6±308.3 <sup>a</sup>                       | 35.1±6.9 <sup>a</sup>           | 7.5±1.1 <sup>a</sup>            |
| Composted horse manure + Struvite + K | 2170.4±362.9 <sup>a</sup>                       | 34.8±6.6 <sup>a</sup>           | 7.4±1.4 <sup>a</sup>            |
| Horse manure + AN + Struvite + K      | 1853.4±231.3 <sup>a</sup>                       | 30.9±3.2 <sup>a</sup>           | 6.3±0.6 <sup>a</sup>            |
| Struvite + AN + K                     | 2012.8±133.1 <sup>a</sup>                       | 32.8±4.2 <sup>a</sup>           | 7.0±4.2 <sup>a</sup>            |
| <i>Prob &gt; F</i>                    | <i>ns</i>                                       | <i>ns</i>                       | <i>ns</i>                       |

Unfertilized (CON), mineral fertilizers (MF) and RNF and mineral fertilizer combinations. Different letters indicate significant differences between treatments at  $p < 0.05$  with the Tukey-Kramer (HSD) test. ns- not significant

No statistically significant differences in winter wheat grain yield were observed among the treatments. Although numerical variation was present, the differences were small relative to within-treatment variability and therefore not considered reliable indicators of treatment effects. Similar patterns were observed for grain P and N concentration, all of which remained comparable across treatments. Overall, the results indicate that winter wheat performance was not significantly influenced by the residual nutrients from the different fertilizer regimes applied in the previous season.

## Effects of RNF fertilizers on soil physico-chemical properties on broccoli plots in 2025

The effects of RNF fertilizers on soil parameters in broccoli plots in 2025 are presented in Table 11. Before fertilization in June 2025, all treatments showed comparable nutrient levels, and no statistically meaningful differences were observed. This indicates that the initial soil conditions were uniform and that any subsequent changes could be attributed to the applied fertilizers rather than to initial soil variability.

**Table 11. Soil chemical characteristics in soil 0-20cm layers at three sampling time under different fertilizer treatments on broccoli plots in 2025 (mean  $\pm$  SD, n=3).**

| Treatment                              |  | pH <sub>KCl</sub> | P<br>mg kg <sup>-1</sup> | S<br>mg kg <sup>-1</sup> | Corg<br>%         | NO <sub>3</sub> -N<br>mg kg <sup>-1</sup> | NH <sub>4</sub> -N<br>mg kg <sup>-1</sup> | TPF<br>( $\mu$ g/g/h) |
|--|--|-------------------|--------------------------|--------------------------|-------------------|---|---|-----------------------|
| Before<br>fertilization<br>(June)      | CON  | 6.10 <sup>a</sup> | 56.67 <sup>a</sup>       | 5.47 <sup>a</sup>        | 2.73 <sup>a</sup> |   |   | 6.93 <sup>a</sup>     |
|  | MF   | 6.13 <sup>a</sup> | 55.67 <sup>a</sup>       | 5.60 <sup>a</sup>        | 2.73 <sup>a</sup> |   |   | 5.31 <sup>a</sup>     |
|  | Digestate liquid<br>fraction<br>(+ struvite + K)                                     | 6.03 <sup>a</sup> | 54.67 <sup>a</sup>       | 4.80 <sup>a</sup>        | 2.70 <sup>a</sup> |   |   | 7.29 <sup>a</sup>     |
|  | Digestate solid<br>fraction<br>(+ struvite + K)                                      | 6.13 <sup>a</sup> | 55.67 <sup>a</sup>       | 4.97 <sup>a</sup>        | 2.77 <sup>a</sup> |   |   | 6.30 <sup>a</sup>     |
|  | Struvite + AN + K  | 6.03 <sup>a</sup> | 52.67 <sup>a</sup>       | 4.73 <sup>a</sup>        | 2.67 <sup>a</sup> |   |   | 6.27 <sup>a</sup>     |
|  | Digestate liquid<br>fraction<br>+ H <sub>2</sub> SO <sub>4</sub> (+ struvite +<br>K) | 6.07 <sup>a</sup> | 52.00 <sup>a</sup>       | 5.17 <sup>a</sup>        | 2.73 <sup>a</sup> |   |   | 6.44 <sup>a</sup>     |
|  | <i>Prob &gt; F</i>   | <i>ns</i>         | <i>ns</i>                | <i>ns</i>                | <i>ns</i>         |   |   | <i>ns</i>             |
| During<br>broccoli<br>growth<br>(July) | CON  | 6.07 <sup>a</sup> | 57.67 <sup>a</sup>       | 5.27 <sup>b</sup>        | 2.70 <sup>a</sup> | 5.30 <sup>a</sup>                         | 1.37 <sup>a</sup>                         | 7.45 <sup>a</sup>     |
|  | MF   | 5.97 <sup>a</sup> | 63.67 <sup>a</sup>       | 5.83 <sup>b</sup>        | 2.67 <sup>a</sup> | 4.43 <sup>a</sup>                         | 1.27 <sup>a</sup>                         | 6.50 <sup>a</sup>     |
|  | Digestate liquid<br>fraction<br>(+ struvite + K)                                     | 6.07 <sup>a</sup> | 62.00 <sup>a</sup>       | 5.67 <sup>b</sup>        | 2.80 <sup>a</sup> | 6.13 <sup>a</sup>                         | 1.43 <sup>a</sup>                         | 7.50 <sup>a</sup>     |
|  | Digestate solid<br>fraction<br>(+ struvite + K)                                      | 6.07 <sup>a</sup> | 60.33 <sup>a</sup>       | 6.47 <sup>b</sup>        | 2.77 <sup>a</sup> | 4.80 <sup>a</sup>                         | 1.27 <sup>a</sup>                         | 7.43 <sup>a</sup>     |
|  | Struvite + AN + K  | 6.03 <sup>a</sup> | 58.33 <sup>a</sup>       | 5.57 <sup>b</sup>        | 2.67 <sup>a</sup> | 5.27 <sup>a</sup>                         | 1.23 <sup>a</sup>                         | 7.10 <sup>a</sup>     |
|  | Digestate liquid<br>fraction<br>+ H <sub>2</sub> SO <sub>4</sub> (+ struvite +<br>K) | 5.93 <sup>a</sup> | 62.33 <sup>a</sup>       | 17.03 <sup>a</sup>       | 2.67 <sup>a</sup> | 5.47 <sup>a</sup>                         | 1.43 <sup>a</sup>                         | 7.22 <sup>a</sup>     |
|  | <i>Prob &gt; F</i>   | <i>ns</i>         | <i>ns</i>                | <i>&lt;.0001</i>         | <i>ns</i>         | <i>ns</i>                                 | <i>ns</i>                                 | <i>ns</i>             |
| After<br>harvest<br>(August)           | CON  | 6.07 <sup>a</sup> | 55.67 <sup>a</sup>       | 4.33 <sup>b</sup>        | 2.77 <sup>a</sup> | 4.57 <sup>a</sup>                         | 1.47 <sup>a</sup>                         | 7.48 <sup>a</sup>     |
|  | MF   | 5.93 <sup>a</sup> | 60.00 <sup>a</sup>       | 4.93 <sup>b</sup>        | 2.70 <sup>a</sup> | 4.00 <sup>a</sup>                         | 1.57 <sup>a</sup>                         | 6.03 <sup>a</sup>     |
|  | Digestate liquid<br>fraction<br>(+ struvite + K)                                     | 6.10 <sup>a</sup> | 56.00 <sup>a</sup>       | 4.93 <sup>b</sup>        | 2.80 <sup>a</sup> | 5.00 <sup>a</sup>                         | 1.80 <sup>a</sup>                         | 7.69 <sup>a</sup>     |
|  | Digestate solid<br>fraction<br>(+ struvite + K)                                      | 6.07 <sup>a</sup> | 56.67 <sup>a</sup>       | 4.70 <sup>b</sup>        | 2.73 <sup>a</sup> | 4.67 <sup>a</sup>                         | 1.27 <sup>a</sup>                         | 7.00 <sup>a</sup>     |
|  | Struvite + AN + K  | 6.00 <sup>a</sup> | 57.00 <sup>a</sup>       | 4.73 <sup>b</sup>        | 2.70 <sup>a</sup> | 4.03 <sup>a</sup>                         | 1.37 <sup>a</sup>                         | 6.13 <sup>a</sup>     |
|  | Digestate liquid<br>fraction<br>+ H <sub>2</sub> SO <sub>4</sub> (+ struvite +<br>K) | 5.93 <sup>a</sup> | 58.00 <sup>a</sup>       | 10.30 <sup>a</sup>       | 2.70 <sup>a</sup> | 4.60 <sup>a</sup>                         | 1.43 <sup>a</sup>                         | 7.56 <sup>a</sup>     |
|  | <i>Prob &gt; F</i>   | <i>ns</i>         | <i>ns</i>                | <i>&lt;.0001</i>         | <i>ns</i>         | <i>ns</i>                                 | <i>ns</i>                                 | <i>ns</i>             |

Unfertilized (CON), mineral fertilizers (MF) and RNF and mineral fertilizer combinations. Different letters indicate significant differences between treatments at  $p < 0.05$  with the Tukey-Kramer (HSD) test. ns- not significant

During broccoli growth in July 2025, some differences became apparent among treatments. Most nutrient concentrations fluctuated only slightly, reflecting natural seasonal dynamics rather than clear treatment effects. However, the treatment using acidified digestate liquid fraction resulted in a markedly higher sulphur (S) concentration (17.03 mg kg<sup>-1</sup>) compared with all other treatments. This increase clearly reflects the direct addition of sulphur through the acidification process.

After harvest of broccoli in August 2025, the acidified digestate treatment again displayed the highest S concentration (10.30 mg kg<sup>-1</sup>). As observed in July, Na concentrations in all digestate fertilizer variants remained significantly higher than in other treatments.

### 3.1.6. Conclusions

#### 2024

Recycled nutrient fertilizer (RNF) combination with mineral fertilizers, such as Struvite + AN + K, showed potential for promoting broccoli growth and phosphorus uptake, but its efficiency was lower than that of mineral fertilizers treatment (MF). The higher efficiency of phosphorus uptake in the Struvite + AN + K treatment, compared to the treatment where struvite was included but most nitrogen came from manure or compost, can be attributed to the more controlled and readily available nitrogen sources in the AN-based fertilizer, which promote better phosphorus uptake and overall plant growth.

Likely, phosphorus uptake from Struvite is largely linked to the availability of nitrogen. The results suggest that when higher amounts of nitrogen were supplied in organic forms, the phosphorus uptake by plants was significantly lower. This indicates that an optimal balance of nitrogen availability is crucial for efficient phosphorus utilization. Based on the results, it was also found that P uptake by plants was higher in the treatments where the sulphur, applied with fertilizer, exceeded 20 kg ha<sup>-1</sup>.

This field trial provides valuable insights into the efficacy of different fertilizers and their impact on crop yield, nutrient efficiency, and soil health. The results suggest that while RNFs may offer environmental benefits, their nutrient availability and efficiency may require further optimization to match the performance of conventional mineral fertilizers.

#### 2025

Recycled nutrient fertilizers (RNFs), particularly when combined with mineral nitrogen sources (e.g. Struvite + AN + K), showed clear potential to support broccoli growth and nutrient uptake in 2025; however, their performance remained generally lower and more variable compared to mineral fertilizer (MF).

At the early growth stage (July), no statistically significant differences were observed in biomass yield or N and P uptake among treatments, despite noticeable numerical variation. Treatments such as digestate liquid fraction and Struvite + AN + K achieved biomass and nutrient uptake levels comparable to MF, indicating that RNFs can supply nutrients effectively during vegetative growth. However, the lack of statistical significance suggests that nutrient release from RNFs may be less synchronized with early plant demand.

By the final harvest (August), fertilizer effects became significant. MF produced the highest broccoli head yield and the greatest N and P uptake, confirming the advantage of readily available mineral nutrients. RNF-based treatments resulted in intermediate yields and nutrient uptake, consistently outperforming the unfertilized control but not differing significantly among themselves.

This indicates that while RNFs can improve productivity, their efficiency remains lower than that of mineral fertilizers under the studied conditions.

A clear positive relationship between yield and nutrient uptake (both N and P) was observed, highlighting that improved nutrient availability directly enhanced biomass production. Like 2024, the results suggest that phosphorus uptake is closely linked to nitrogen availability, with treatments supplying more readily available N (e.g. AN-based combinations) achieving higher P uptake.

In terms of residual effects, no statistically significant differences were observed in winter wheat yield or nutrient uptake among treatments following the broccoli experiment. Although slight numerical variation occurred, grain yield, as well as N and P uptake, remained comparable across all treatments. This suggests that, similarly to the 2024 findings, the residual impact of both RNFs and mineral fertilizers on the subsequent crop was limited, and most of the applied nutrients were utilized during the broccoli growing season.

Regarding soil properties, most parameters (pH, P, Corg,  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ , DHA) were not significantly affected by treatments. The only consistent effect was observed for sulphur (S), which was significantly higher in the acidified digestate treatment due to direct S input. However, this increase did not translate into improved crop yield or nutrient uptake.

Overall, the 2025 results confirm that while RNFs can partially substitute mineral fertilizers and support crop production, their nutrient availability and efficiency, particularly in relation to nitrogen supply and its interaction with phosphorus uptake-require further optimization to achieve performance comparable to conventional mineral fertilization.

## 3.2. Poland

### 3.2.1 Methodology

#### Experimental design

In 2024 and 2025, three field experiments were conducted at the IUNG Agricultural Experimental Station in Grabów (ES Grabów) [51°21'18"N 21°40'09"E] using a consistent experimental layout. The trials focused on two main crops, with a transition in the wheat experiments from spring wheat in 2024 to winter wheat in 2025, while maize grown for silage was cultivated consistently during both growing seasons. Regarding the application of fertilizers, "mineral" RNF products were tested on both wheat and maize plots, whereas "organic" RNF fertilizers were utilized exclusively for the maize trials. All experiments were established as single-factor trials following a long strip design with a mirror-image layout, utilizing four replications for each tested fertilizer to ensure the statistical reliability of the results across both years of the study.

For the 'mineral' RNF, an assessment of its effect on crop yield was planned in comparison to standard mineral fertilization, while 'organic' RNF was tested in comparison to the object in which manure was used. In the experiment, two 'mineral' (struvite and ammonium sulfate liquid) and one 'organic' (digestate pellet) RNFs were tested, and the experimental design included 6 and 4 treatments, respectively. The schemes of field experiments with the objects listed are shown in the table 12 and 13 below.

**Table 12. Experimental scheme for 'mineral' RNF with spring wheat and maize silage**

| Repetition 1 |   |   |   |   |   | Repetition 2 |   |   |   |   |   |
|--------------|---|---|---|---|---|--------------|---|---|---|---|---|
| A            | B | C | D | E | F | F            | E | D | C | B | A |
| A            | B | C | D | E | F | F            | E | D | C | B | A |
| Repetition 3 |   |   |   |   |   | Repetition 4 |   |   |   |   |   |

- A – 50% of the expected N demand delivered by standard nitrogen fertilizer (NH<sub>4</sub>NO<sub>3</sub>), P, and K as 100%
- B – 100% of expected N demand delivered by standard nitrogen fertilizer (NH<sub>4</sub>NO<sub>3</sub>), P, and K as 100% (control)
- C – 125% of the expected N demand delivered by standard nitrogen fertilizer (NH<sub>4</sub>NO<sub>3</sub>), P, and K as 100%
- D – ASL – 100% nitrogen delivered by ASL, P, and K as in the control
- E – Struvite – 100% phosphorus delivered by struvite, N by standard nitrogen fertilizer (NH<sub>4</sub>NO<sub>3</sub> - N in struvite) and K as in control
- F – ASL + Struvite – 100% nitrogen delivered by (ASL + Struvite) and 100% P delivered by struvite, K as in control

**Table 13. Experimental scheme for 'organic' RNF with maize silage**

| Repetition 1 |   |   |   | Repetition 2 |   |   |   |
|--------------|---|---|---|--------------|---|---|---|
| A            | B | C | D | D            | C | B | A |
| A            | B | C | D | D            | C | B | A |
| Repetition 3 |   |   |   | Repetition 4 |   |   |   |

A – control without nitrogen fertilization (0 kg N), P and K as 100%

B – 25% of the expected N (45kg) demand delivered by standard nitrogen fertilizer (NH<sub>4</sub>NO<sub>3</sub>), P and K as 100%

C – 'organic' NFR (Planteo pellet); 9 t ha<sup>-1</sup> (~ 45kg N)

D – dairy cow manure; 33 t ha<sup>-1</sup> (~ 45kg N)

### Fertilizers

In the field experiments, two mineral fertilizers: ammonium sulfate liquid (ASL) and struvite and one organic fertilizer pelletized digestate. ASL is a nitrogen-sulfur fertilizer produced during the anaerobic fermentation of organic raw materials, which takes place in the biorefineries of the VERBIO AG corporation. Struvite is a phosphorus-magnesium-nitrogen fertilizer produced from the liquid fraction of sludge by the Soepenbergl company (partner in the project). Planteo pelleted digestate is the only organic fertilizer produced from a solid digestate fraction that uses 100% plant feed for the anaerobic digestion process by the Zielone Suszarnie company.

All fertilizers (mineral and organic) in the experiment were applied manually and spread evenly on the plot surface in appropriate amounts before sowing and then mixed with the top layer of soil to approximately a depth. Nitrogen was applied in two divided doses - 60% N before sowing and 40% at the shooting stage (BBCH 31-32) in wheat and at the 5-6 leaf stage (BBCH 15-16) in maize and in an appropriate form (ASL or ammonium nitrate). Phosphorus was applied as struvite or single-component phosphorus fertilizer, depending on the treatment. Potassium in all treatments was delivered in the potassium salt. Nutrient rates used in experiments are presented in Table 14.

**Table 14. Standard nutrient rates in field trails depending on the crop**

| Nutrient                      | Spring wheat           | Winter wheat            | Silage maize            |
|-------------------------------|------------------------|-------------------------|-------------------------|
| N                             | 90 kg ha <sup>-1</sup> | 150 kg ha <sup>-1</sup> | 180 kg ha <sup>-1</sup> |
| P <sub>2</sub> O <sub>5</sub> | 40 kg ha <sup>-1</sup> | 70 kg ha <sup>-1</sup>  | 80 kg ha <sup>-1</sup>  |
| K <sub>2</sub> O              | 60 kg ha <sup>-1</sup> | 110 kg ha <sup>-1</sup> | 180 kg ha <sup>-1</sup> |

### Observations and sampling during vegetation

During vegetation in all experiments, SPAD measurements were performed three times. In spring wheat, SPAD was measured at the shooting stage (BBCH 31-32), the earing stage (BBCH 53-55), and the early milk stage (BBCH 73), while in maize – at the 5-6th leaf stage (BBCH 15-16), 2nd node stage (BBCH 32) and tasselling stage (BBCH 53-55).

Soil samples were taken twice during vegetation: before setting up the experiment, one collective soil sample was taken, and after harvesting the plants, soil samples were taken from all

experimental treatments. Soil analyses included pH, Corg, P (Egner-Riehm and Mehlich 3 method), K, and S i Nmin. In the 'organic' RNF trial, microbiological analyses were also performed: soil microbial biomass, soil enzymes (soil acid and alkaline phosphates, and dehydrogenases), and soil organic matter analyses: total organic carbon content (Corg), fraction of humic substances (fulvic and humic acids, humins).

Plant samples were collected three times during vegetation in the same developing stages as SPAD measurements from an area of 2 m<sup>2</sup> for wheat and from a 4 m length (28 plants) for maize. During the harvest, the yield of plants was determined, which for wheat was determined from an area of 80 m<sup>2</sup> and for maize from an area of 60 m<sup>2</sup>. In the dry mass of plants collected both during the vegetation period and at the harvest, the content of nutrients such as N, P, K, and S.

### Statistical analysis

Statistical analysis of the results was performed using the Statgraphics Centurion 18 software package (Statgraphics Technologies, Inc., The Plains, Virginia, USA). Analysis of variance (ANOVA) was applied, and the significance of differences between means was determined using Tukey's test at a significance level of  $\alpha = 0.05$ .

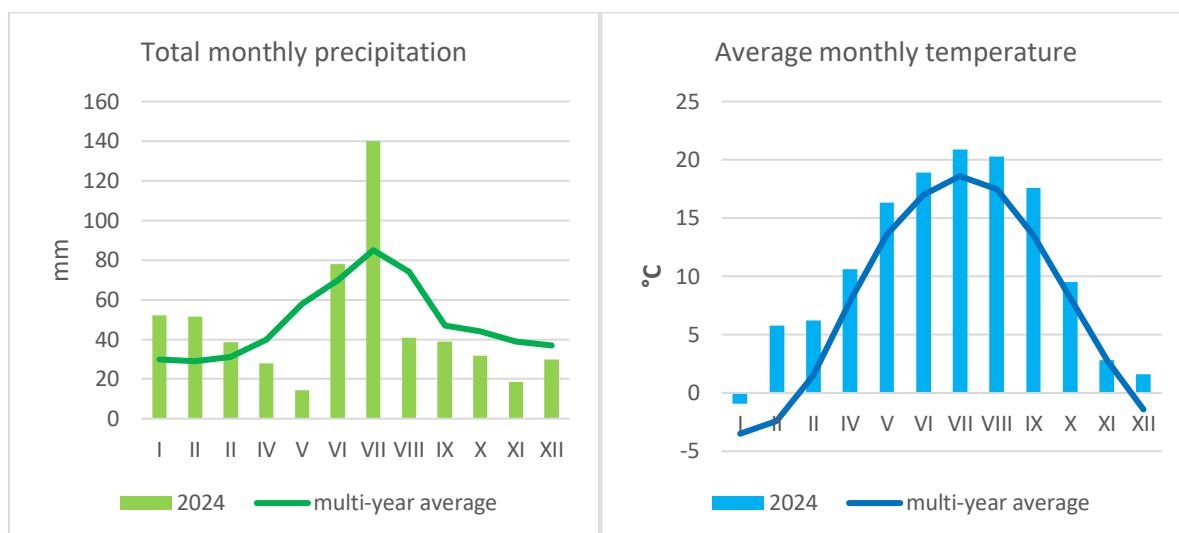
### 3.2.2. Weather conditions

#### 2024

In the 2024 growing season (Fig. 10), i.e., from April to September, drought periods and periods with significantly higher rainfall than the multi-annual average were recorded at the IUNG Agricultural Experimental Station in Grabów. The mentioned water shortages and drought periods usually appear in this region at the turn of June and July. However, in 2024, they occurred much earlier. In April, less than 28 litres of water fell, and this precipitation was recorded mainly in the first ten days of the month. In May, at the end of the month, rainfall amounted to 14.3 mm. This year (2024), even winter crops felt the water deficit, which, due to the rather wet autumn of 2023, did not develop a very large root system; their development was inhibited. The plants were quite short. The situation was even worse in spring cereals. The drought caused a significant acceleration of the ripening of crop plants by up to 2-3 weeks, and in many stalks, the ear stopped in the leaf sheath, and this is where the flowering phase occurred. This was the main reason for the low yield level of spring cereals.

After the water shortages in April and May, rains came in June, which significantly improved soil moisture conditions. The average rainfall norm was exceeded during the two decades of the month. This rainfall no longer helped to obtain high yields of cereals, rapeseed and legumes, but it had a positive effect on the growth and development and yield of maize. The yields obtained in most of the fields with maize cultivation in the ES Grabów were quite high.

In contrast to the average monthly precipitation, the average monthly temperature was less variable compared to the multi-year average. In the growing season (from April to September), higher average monthly temperatures were observed by about 2°C compared to the multi-year data (Fig. 4). This, combined with periodic low rainfall, caused unfavorable conditions for growing spring cereals, but higher temperatures had a positive effect on maize cultivation.

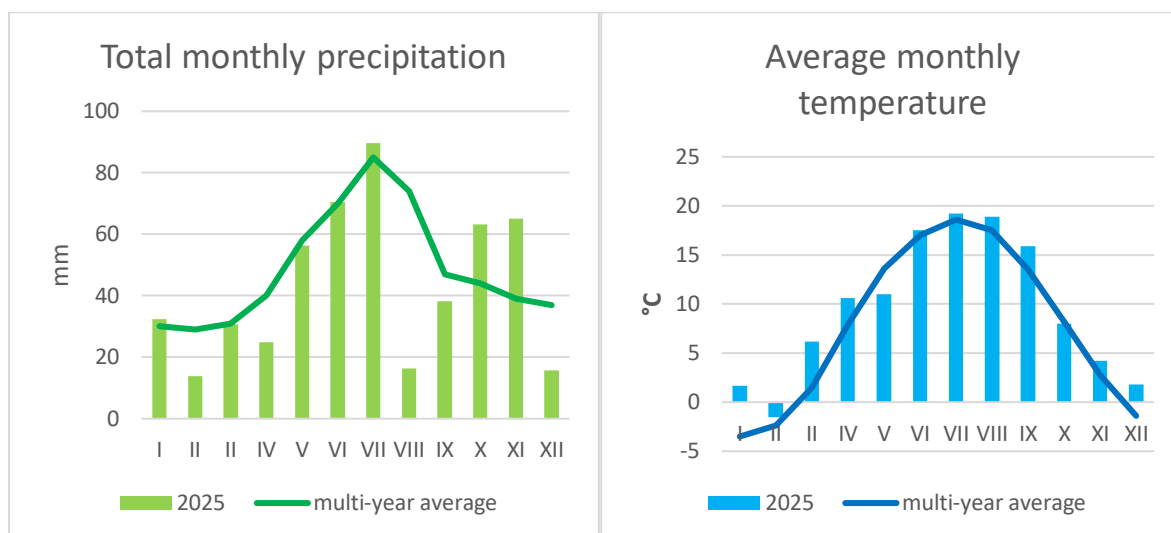


**Figure 10. Average monthly precipitation and temperature in ES Grabów in 2024 compared to the multi-year average**

## 2025

Autumn 2024 was relatively mild, with warm and fairly dry conditions (Fig. 11). Monthly precipitation did not exceed long-term averages. The winter period was marked by drought and a lack of snow cover. While January brought 32.3 mm of rainfall, which corresponds to the long-term norm for this month, precipitation in February was significantly lower. In the second decade of February, a sharp drop in temperature occurred, with minimum values reaching  $-16^{\circ}\text{C}$ . This raised concerns about the condition of winter crops. However, field inspections carried out at the end of the month confirmed that the frost had not caused any damage, either in commercial fields or in the experimental plots.

May was a relatively cool month, with an average temperature of  $11.0^{\circ}\text{C}$  —  $2.6^{\circ}\text{C}$  below the long-term mean. The most severe ground frost occurred around 9 May ( $-4.3^{\circ}\text{C}$ ). In contrast, precipitation totals in May (56.3 mm), June (70.4 mm), and July (89.7 mm) were close to long-term averages (58, 70, and 85 mm, respectively). The cool conditions in May did not slow the development of the cultivated crops. Disease and pest pressure were also lower than in previous years. In June, as in May, rainfall remained close to the long-term norm, while temperatures were higher than average. The precipitation deficit was not substantial, providing generally favourable conditions for the growth and development of winter crops. It was only in August that a marked decline in rainfall was recorded — just 16.4 mm — which accelerated crop maturation.



**Figure 11. Average monthly precipitation and temperature in ES Grabów in 2025 compared to the multi-year average**

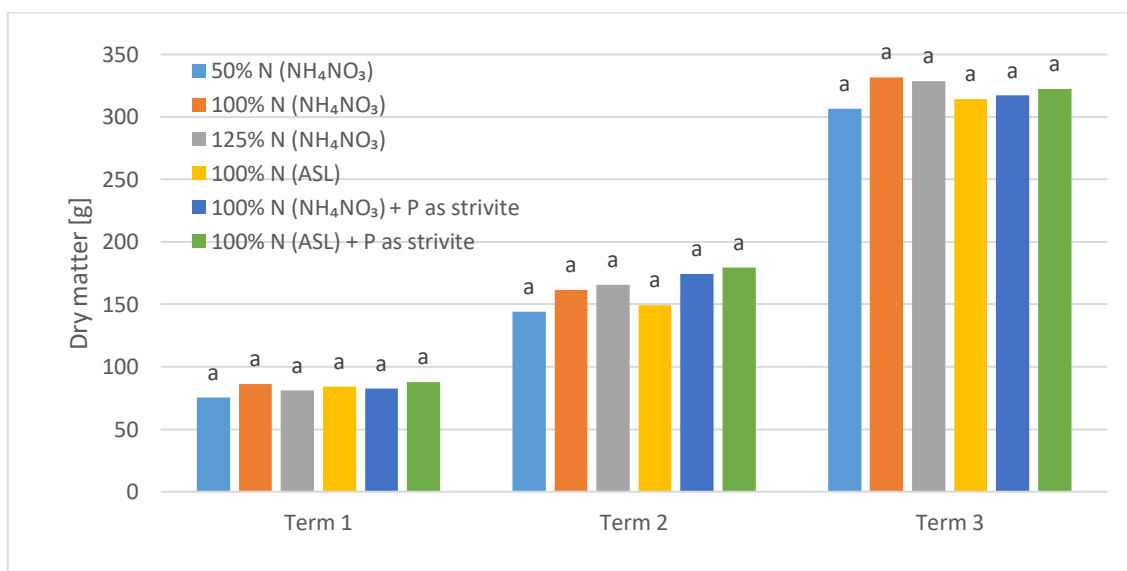
### 3.2.3. Results

#### 'Mineral' RNF

#### Spring Wheat (2024 season)

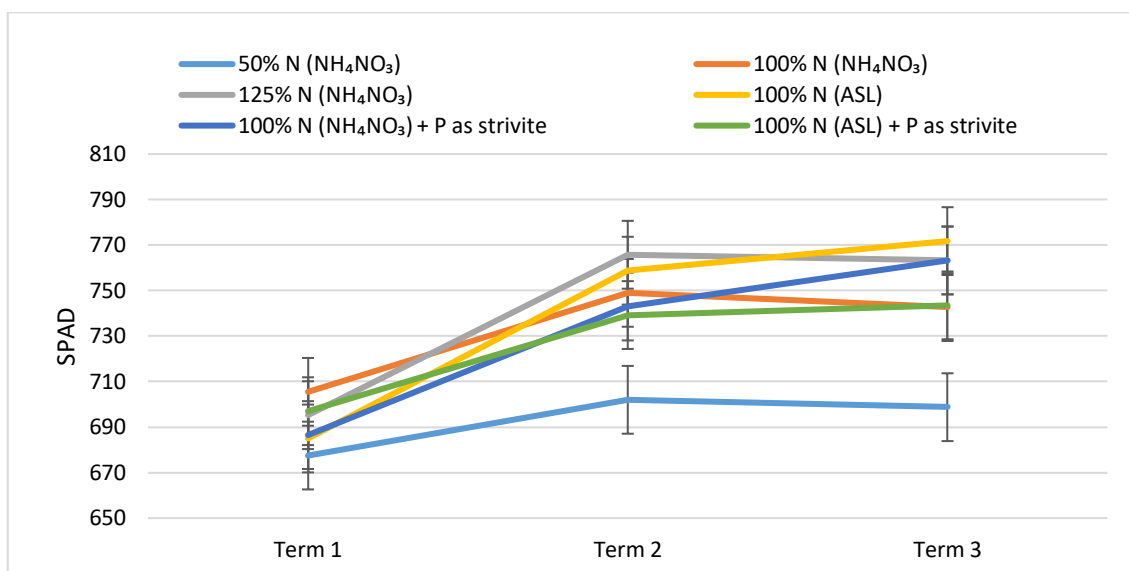
#### Biomass accumulation and SPAD measurements during vegetation

In 2024, the growth of spring wheat was greatly influenced by weather conditions, which significantly limited biomass accumulation during the growing season and made it difficult to interpret the obtained results. During the growing season, no significant differences in the yield of dry plant mass were observed between the treatments at any of the sampling dates (Fig. 12).



**Figure 12. Spring wheat biomass accumulation from a 2 m<sup>2</sup> area during vegetation (the shooting stage (BBCH 31-32), the earing stage (BBCH 53-55), and the early milk stage (BBCH 73)).**

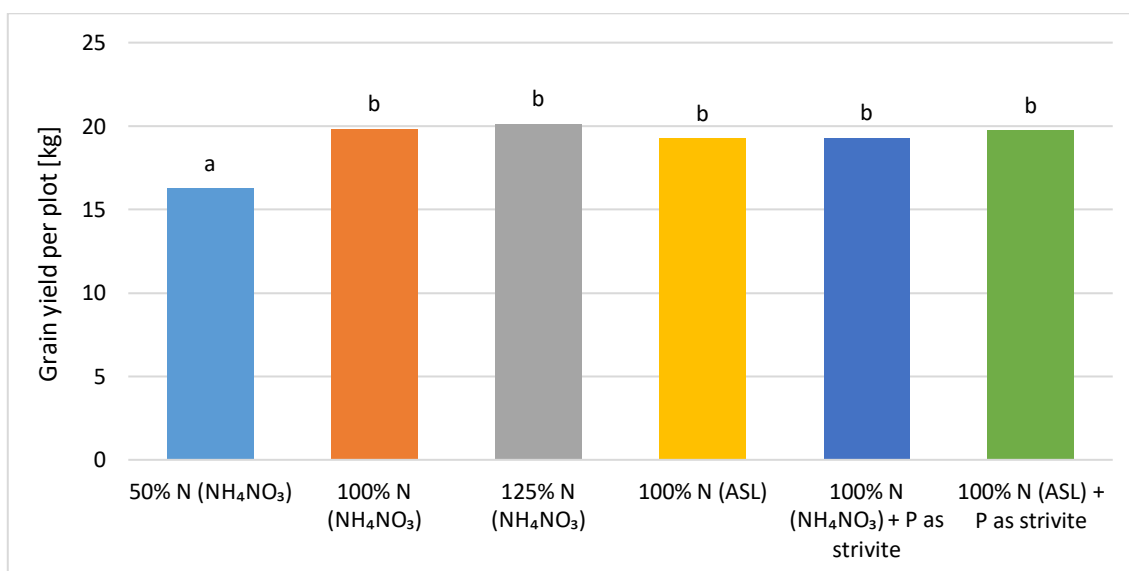
In the first measurement date of the SPAD index (BBCH 31-32), no differences were found between the treatments (Fig. 13). In the second (BBCH 53-55) and third (BBCH 73) measurement dates, a lower SPAD value was observed in the treatment with nitrogen fertilization reduced by 50%. However, no differences were found between the treatments fertilized with ammonium nitrate and ammonium sulphate.



**Figure 13.** Index SPAD was measured in spring wheat during vegetation (the shooting stage (BBCH 31-32), the earing stage (BBCH 53-55), and the early milk stage (BBCH 73).

### Grain yield

The grain yield of spring wheat did not differ between the treatments with a full dose (100%) of nitrogen fertilization, regardless of the form of nitrogen used - ammonium nitrate or ammonium sulphate (Fig. 14). The mean mineral fertilizer replacement value for the object with ASL (D) was calculated at 96.7% of the control treatment (B). A significantly higher yield was observed only between the full and halved doses of nitrogen in the form of ammonium nitrate (treatments A and B). No increase in grain yield was observed as a result of the application of a dose of nitrogen fertilization increased to 125%, which was probably due to unfavorable weather conditions.



**Figure 14.** Spring wheat grain yield from an 80 m<sup>2</sup> plot.

### Nutrient content in the yield

In the analysis of the mineral composition of spring wheat grain, significant differences were observed for nitrogen and sulphur content (Table 15). The highest nitrogen concentration was recorded in treatment C (increased N dose). Notably, no significant differences were observed between treatments receiving the full nitrogen dose, regardless of the fertilizer form applied (B, D,

E). Regarding sulphur, significantly higher concentrations were observed in treatments D and F (fertilized with ASL) compared to treatment A. No statistically significant variances were detected for phosphorus or potassium content across the studied treatments.

**Table 15. Nutrient content in spring wheat grain**

| Treatment  | N      | P     | K     | S      |
|--|--------|-------|-------|--------|
|  | %      |       |       |        |
| A. 50% N (NH <sub>4</sub> NO <sub>3</sub> )                  | 2.42c  | 0.44a | 0.54a | 0.12b  |
| B. 100% N (NH <sub>4</sub> NO <sub>3</sub> )                 | 2.67b  | 0.44a | 0.55a | 0.13ab |
| C. 125% N (NH <sub>4</sub> NO <sub>3</sub> )                 | 2.97a  | 0.48a | 0.59a | 0.13ab |
| D. 100% N (ASL)  | 2.83ab | 0.45a | 0.55a | 0.14a  |
| E. 100% N (NH <sub>4</sub> NO <sub>3</sub> ) + P as strivite | 2.79ab | 0.42a | 0.51a | 0.13ab |
| F. 100% N (ASL) + P as strivite                              | 2.69b  | 0.41a | 0.51a | 0.14a  |

**Effects of the RNF on soil physical-chemical characteristics in 2024**

In the 2024 growing season, significant differences were limited to the soil phosphorus content (Egner-Rhiem method) and mineral nitrogen (Table 16). The highest post-harvest phosphorus concentration was recorded in treatment A, which was significantly higher compared to treatments E and F, supplemented with struvite. Regarding mineral nitrogen, a significantly elevated level of this nutrient was observed in treatment C (125% N dose) relative to all other experimental variants. No statistically significant variances were detected for soil pH, phosphorus determined by the Melich 3 method, potassium, sulphur, or organic carbon content across the studied fertilization treatments.

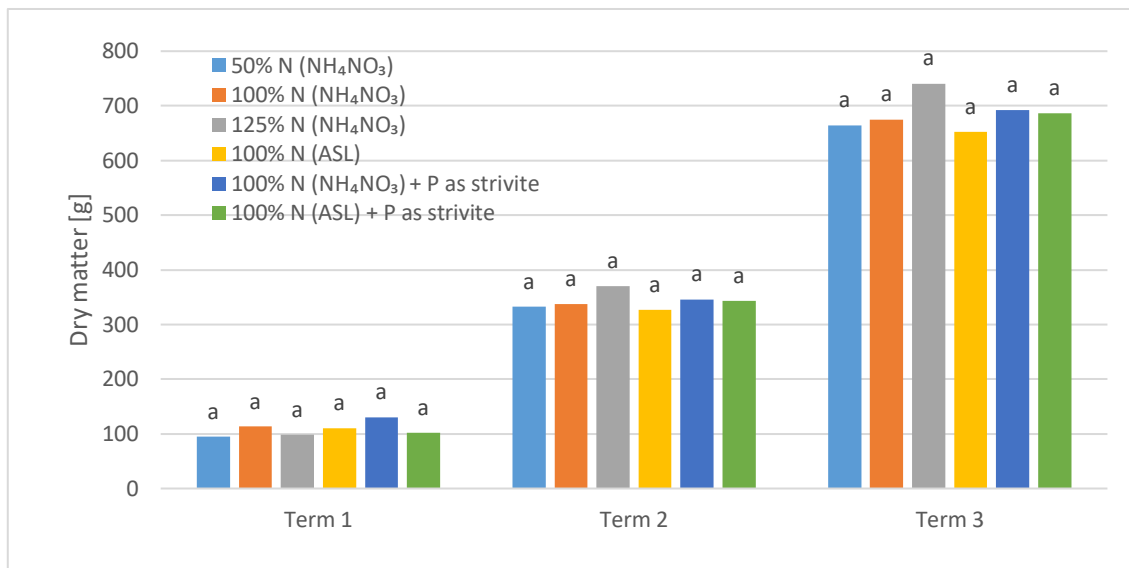
**Table 16. Nutrient content in the soil before sowing and after harvesting spring wheat**

| Treatment            | pH   | P (Egner-Rhiem) | P (Melich 3) | K <sub>2</sub> O | S     | Nmin  | Corg  |       |
|----------------------|--|-----------------|--------------|------------------|-------|-------|-------|-------|
|                      |  | mg/100g of soil |              |                  |       |       |       | (%)   |
| <b>Before sowing</b> | 5.2  | 15.8            | 19.1         | 17.5             | 0.38  | 4.0   | 0.77a |       |
| <b>After harvest</b> | A<br>50% N (NH <sub>4</sub> NO <sub>3</sub> )                    | 5.4a            | 17.7a        | 20.6a            | 15.6a | 0.49a | 7.05a | 0.8a  |
|                      | B<br>100% N (NH <sub>4</sub> NO <sub>3</sub> )                   | 5.2a            | 15.3ab       | 21a              | 17.2a | 0.48a | 7.25a | 0.77a |
|                      | C<br>125% N (NH <sub>4</sub> NO <sub>3</sub> )                   | 5.3a            | 16.0ab       | 21.4a            | 16.3a | 0.49a | 8.08b | 0.69a |
|                      | D<br>100% N (ASL)  | 5.0a            | 15.0ab       | 18.9a            | 16.8a | 0.54a | 7.33a | 0.67a |
|                      | E<br>100% N (NH <sub>4</sub> NO <sub>3</sub> ),<br>P as strivite | 5.0a            | 13.6b        | 18.9a            | 16.4a | 0.50a | 7.37a | 0.71a |
|                      | F<br>100% N (ASL),<br>P as strivite                              | 5.1a            | 13.1b        | 18.2a            | 17.5a | 0.52a | 7.03a | 0.72a |

## Winter Wheat (2025 season)

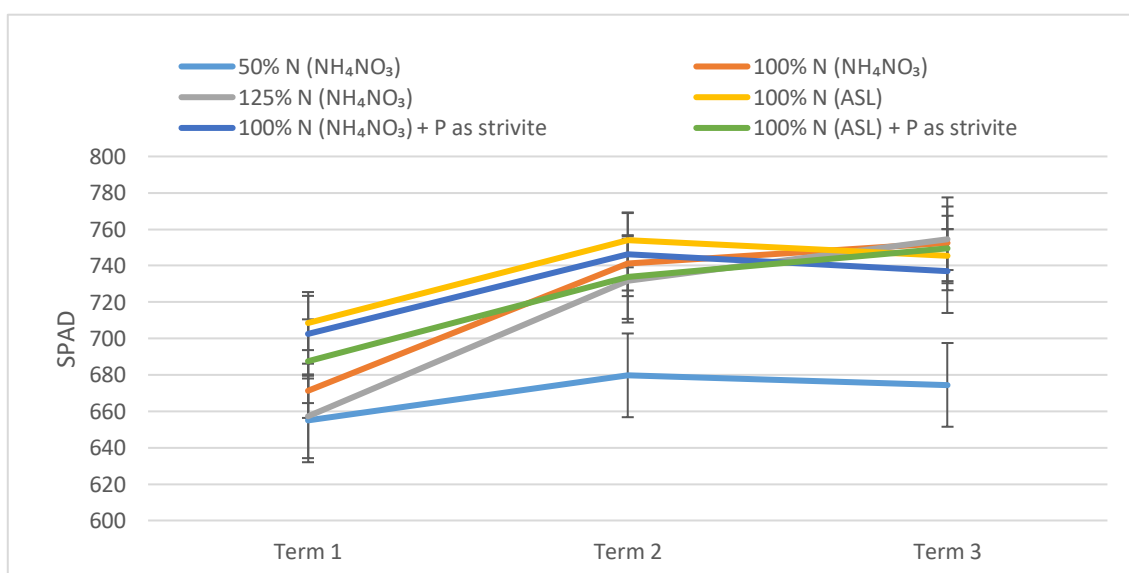
### Biomass accumulation and SPAD measurements during vegetation

In the 2025 season, the dynamics of winter wheat dry matter accumulation were consistent across all sampling dates, and the applied fertilization treatments showed no statistically significant differences in biomass accumulation (Fig. 15).



**Figure 15.** Winter wheat biomass accumulation from a 2 m<sup>2</sup> area during vegetation (the shooting stage (BBCH 31-32), the earing stage (BBCH 53-55), and the early milk stage (BBCH 73)).

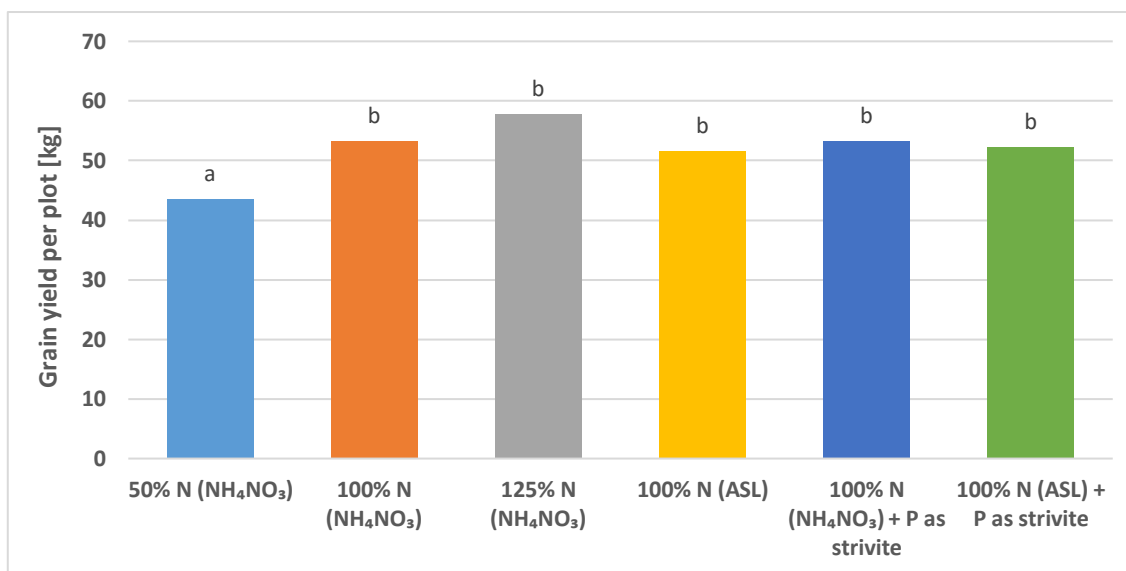
Regarding the SPAD index, no differences between treatments were found at the first measurement date (BBCH 31-32); however, in the later stages (BBCH 53-55 and BBCH 73), significantly lower values were observed in the treatment with the nitrogen dose reduced by 50%. No significant differences in plant nitrogen nutrition were found between the treatments fertilized with ammonium nitrate and ammonium sulphate (Fig. 16).



**Figure 16.** Index SPAD was measured in winter wheat during vegetation (the shooting stage (BBCH 31-32), the earing stage (BBCH 53-55), and the early milk stage (BBCH 73)).

## Grain yield

The grain yield of winter wheat was statistically similar across all treatments receiving a full nitrogen dose (100% N), regardless of the nitrogen form or the addition of phosphorus as struvite (Fig. 17). A significantly lower yield was recorded only in the case of the nitrogen dose reduced to 50%. Increasing the nitrogen dose to 125% did not result in a further statistical increase in yield. The mean mineral fertilizer replacement value for the ASL treatment (D) was calculated at 97.1% relative to the control (B), which is a level similar to that observed for spring wheat.



**Figure 17. Winter wheat grain yield from an 80 m<sup>2</sup> plot.**

## Nutrient content in the yield

In the analysis of the mineral composition of winter wheat grain dry matter, statistically significant differences were observed exclusively for nitrogen content (Table 17). The highest nitrogen concentration was recorded in treatment C (increased N dose), which differed significantly from treatments receiving nitrogen in the form of ASL (D) as well as treatments A and F. Notably, no significant differences were observed between treatments receiving the full nitrogen dose in mineral form (B) and those supplemented with struvite (E). Regarding phosphorus, potassium, and sulphur, no statistically significant variances were detected across the studied treatments.

**Table 17. Nutrient content in winter wheat grain dry matter**

| Treatment  | N       | P     | K     | S     |
|--|---------|-------|-------|-------|
|  | %       |       |       |       |
| A. 50% N (NH <sub>4</sub> NO <sub>3</sub> )                  | 1.77ab  | 0.35a | 0.46a | 0.13a |
| B. 100% N (NH <sub>4</sub> NO <sub>3</sub> )                 | 2.17bc  | 0.36a | 0.49a | 0.14a |
| C. 125% N (NH <sub>4</sub> NO <sub>3</sub> )                 | 2.26c   | 0.37a | 0.50a | 0.14a |
| D. 100% N (ASL)  | 1.71a   | 0.35a | 0.48a | 0.15a |
| E. 100% N (NH <sub>4</sub> NO <sub>3</sub> ) + P as struvite | 2.01abc | 0.38a | 0.51a | 0.14a |
| F. 100% N (ASL) + P as struvite                              | 1.76ab  | 0.39a | 0.47a | 0.16a |

## Effects of the RNF on soil physical-chemical characteristics in 2025

In the 2025 season, the only soil parameter that showed significant differences was the sulphur content (Table 18). The highest post-harvest concentrations of this nutrient were recorded in treatments D and F (fertilized with nitrogen in the form of ASL), which differed significantly from the other fertilization variants. For all other studied parameters, including soil pH, phosphorus content

(determined by both methods), potassium, mineral nitrogen, and organic carbon content, no statistically significant differences were observed among the applied fertilization combinations.

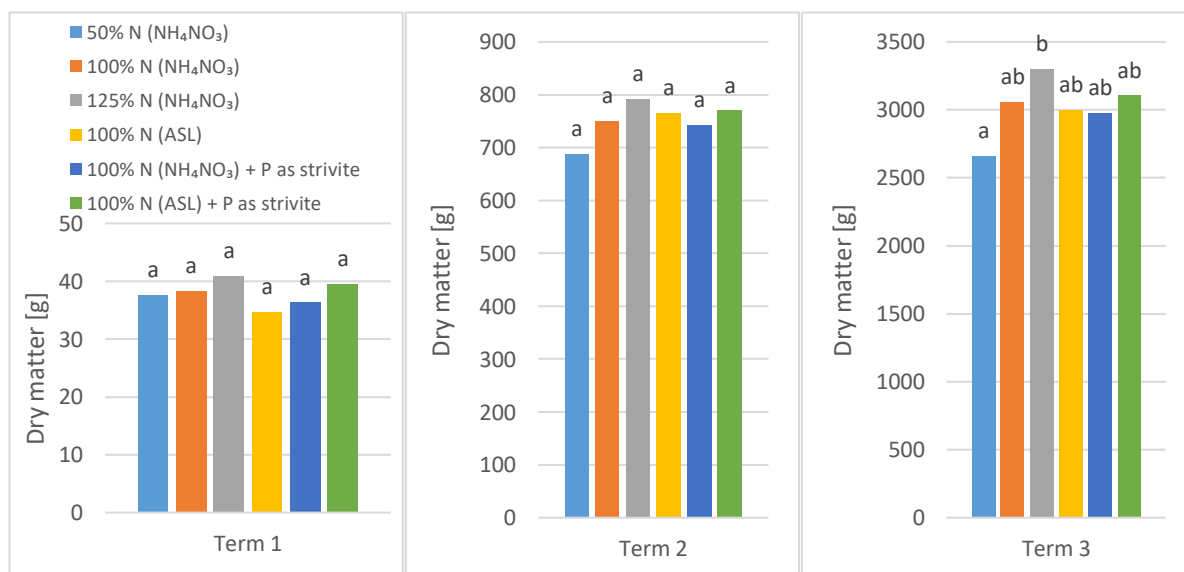
**Table 18. Nutrient content in the soil before sowing and after harvesting winter wheat**

| Treatment            |  | pH   | P<br>(Egner-Rhiem) | P<br>(Melich) | K <sub>2</sub> O | S     | Nmin | Corg  |
|----------------------|--|------|--------------------|---------------|------------------|-------|------|-------|
|                      |  |      | mg/100g of soil    |               |                  |       |      |       |
| <b>Before sowing</b> |  | 5.5  | 14.7               | 14.2          | 13.6             | 0.33  | 8.7  | 0.73  |
| After harvest        | A<br>50% N (NH <sub>4</sub> NO <sub>3</sub> )                    | 5.3a | 13.5a              | 14.2a         | 14.6a            | 0.29a | 8.7a | 0.69a |
|                      | B<br>100% N (NH <sub>4</sub> NO <sub>3</sub> )                   | 5.2a | 12.1a              | 14.1a         | 16.2a            | 0.29a | 8.0a | 0.68a |
|                      | C<br>125% N (NH <sub>4</sub> NO <sub>3</sub> )                   | 5.3a | 15.4a              | 14.1a         | 16.3a            | 0.27a | 7.8a | 0.66a |
|                      | D<br>100% N (ASL)  | 5.1a | 13.1a              | 13.0a         | 13.2a            | 0.49b | 7.5a | 0.66a |
|                      | E<br>100% N (NH <sub>4</sub> NO <sub>3</sub> ),<br>P as strivite | 5.2a | 12.2a              | 15.5a         | 13.4a            | 0.34a | 8.2a | 0.67a |
|                      | F<br>100% N (ASL),<br>P as strivite                              | 5.1a | 15.1a              | 15.6a         | 14.5a            | 0.53b | 8.3a | 0.68a |

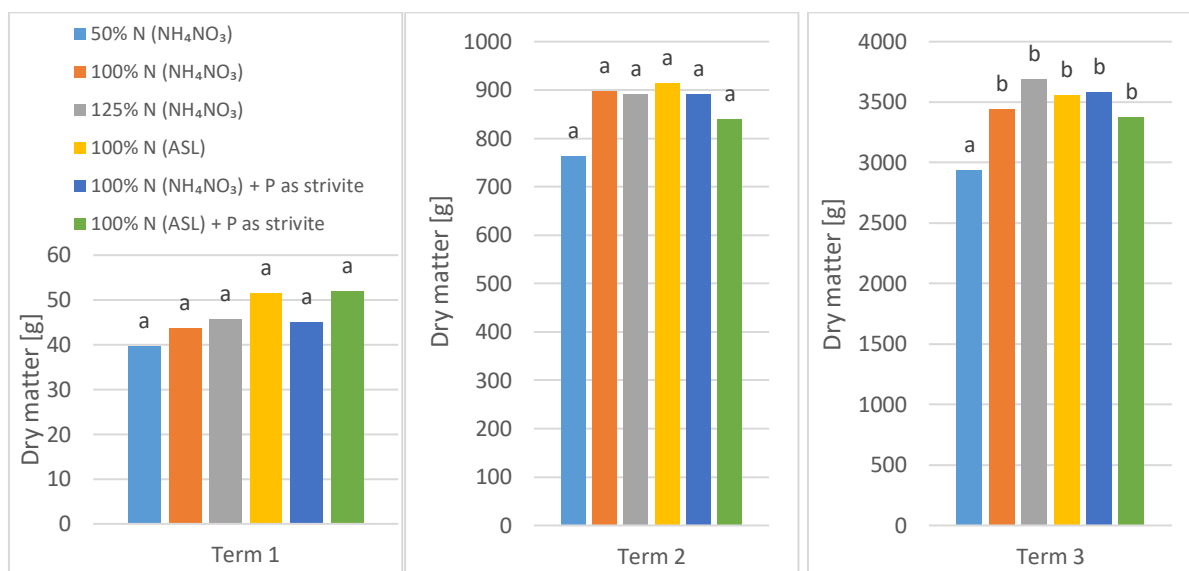
**Maize**

**Biomass accumulation and SPAD measurements during vegetation**

During the vegetation period, no significant effect of fertilizer type on biomass accumulation was observed at any of the sampling dates (Fig. 18). In 2024, a higher dry-matter yield was recorded only at the third sampling date, following the application of the increased nitrogen dose (125%) compared with the reduced dose (50%). In contrast, in 2025, higher biomass accumulation was observed at all sampling dates in the treatments receiving the full or increased nitrogen rate, compared with the reduced-rate treatment (Fig. 19).

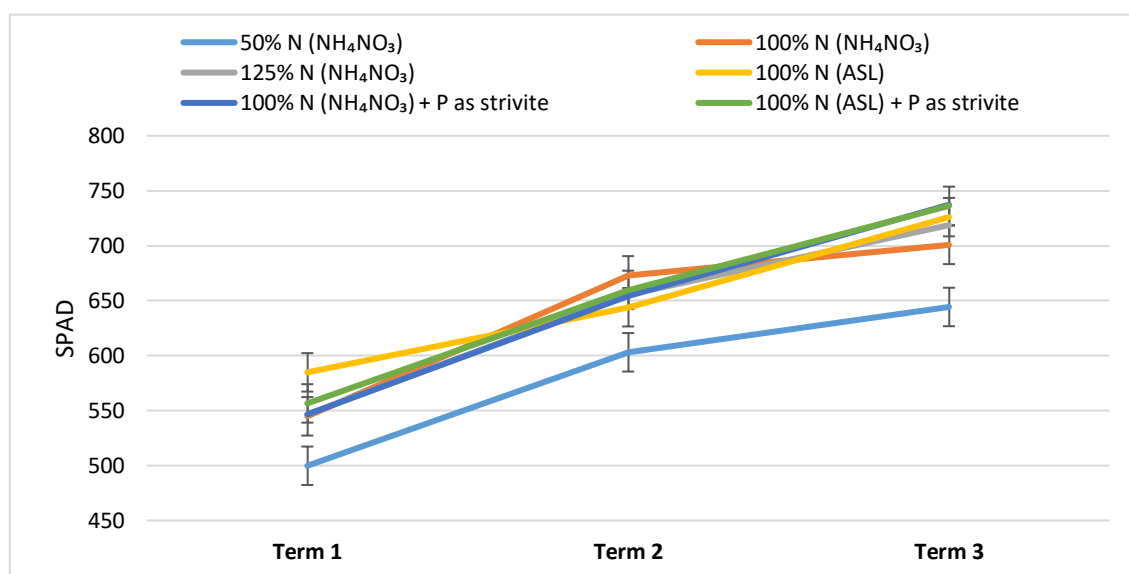


**Figure 18. Maize biomass accumulation during vegetation (5-6th leaf stage (BBCH 15-16), 2nd node stage (BBCH 32) and tasselling stage (BBCH 53-55)) in the 2024 season.**



**Figure 19. Maize biomass accumulation during vegetation (5-6th leaf stage (BBCH 15-16), 2nd node stage (BBCH 32) and tasselling stage (BBCH 53-55)) in the 2025 season.**

In both growing seasons, the SPAD index value was significantly influenced only by the reduced dose (50% N) of nitrogen fertilization, which caused its value to decrease in comparison to the full dose (100% N) and increased dose (125% N) (Fig. 20 and 21). The form of nitrogen used did not affect any of the measurement dates, which can indirectly indicate that the level of nitrogen supply to plants was similar.



**Figure 20. Index SPAD measured in maize during the vegetation (5-6th leaf stage (BBCH 15-16), 2nd node stage (BBCH 32) and tasselling stage (BBCH 53-55)) in the 2024 season.**

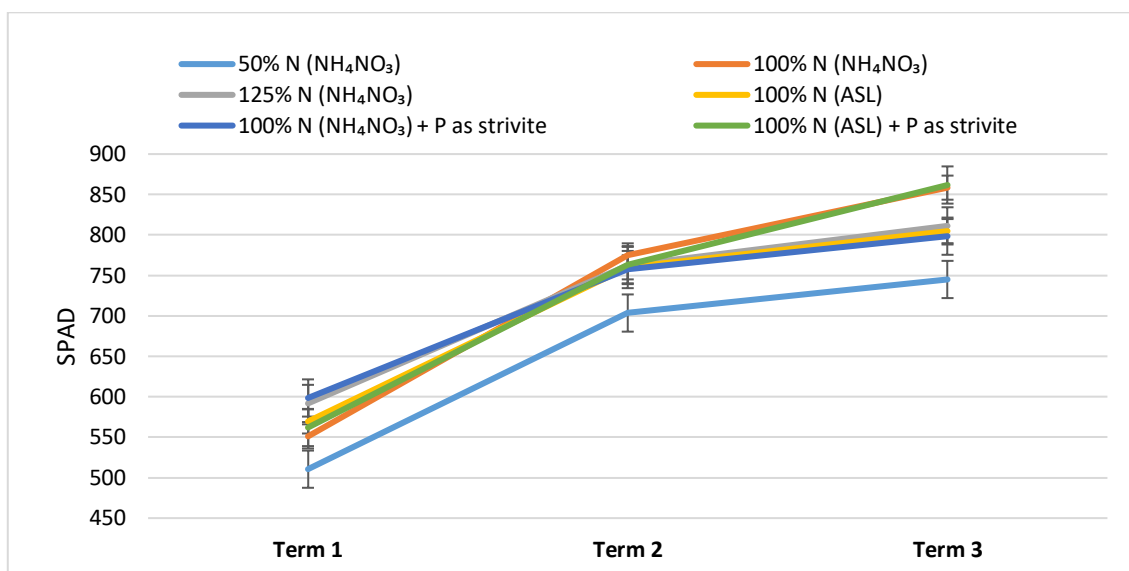


Figure 21. Index SPAD measured in maize during vegetation (5-6th leaf stage (BBCH 15-16), 2nd node stage (BBCH 32) and tasselling stage (BBCH 53-55)) in the 2025 season.

### Silage dry matter yield

The yield of dry matter of silage maize did not depend on the type of nitrogen fertilizer used (Fig. 22). The yield from the plot obtained in the object in which nitrogen was applied in the form of ammonium sulphate (ASL - object D and F) and ammonium nitrate (control treatment) did not differ significantly. The mean of mineral fertilizer replacement value for the object with ASL (D) was calculated at the level of 98.5% of the control object (B) in the 2024 season and at 105.7 in the 2025 season. The higher dry-matter yield of corn silage in 2025 following the application of ammonium sulfate, compared with ammonium nitrate, may result from the positive effect of sulfur supplied in ASL (Fig. 23). A significant increase in yield was observed only in the case of an increase in the nitrogen dose from half the dose (object A) to the full dose (objects B, D, E, F) further increase in fertilization (up to 125% of the N dose - object C) did not cause a significant increase in the maize yield.

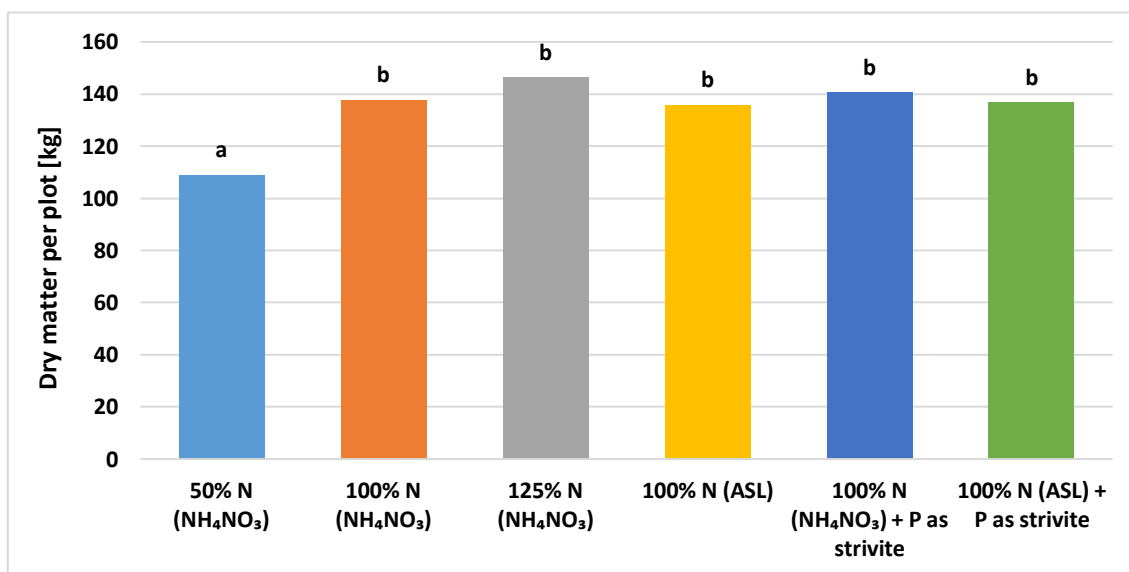


Figure 22. Dry matter yield of maize silage from a 60 m<sup>2</sup> plot in the 2024 season.

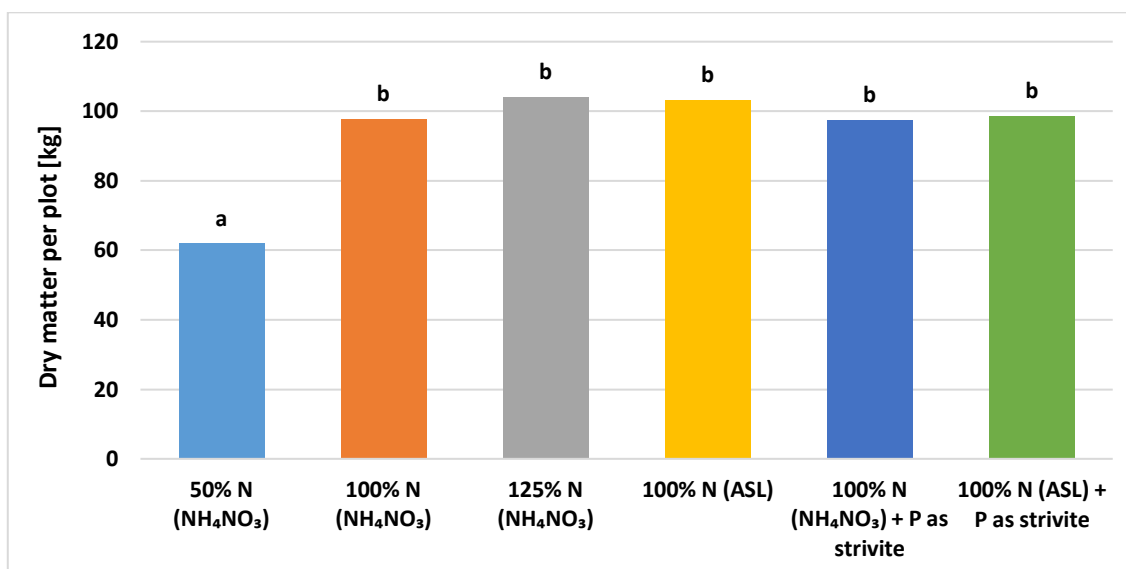


Figure 23. Dry matter yield of maize silage from a 60 m<sup>2</sup> plot in the 2025 season.

### Nutrient content in the yield

In the analysis of the nutrient content in the dry matter of silage maize yield, statistically significant differences were observed exclusively for nitrogen (N) in both growing seasons (Table 19). In the 2024 season, the lowest nitrogen concentration was recorded in treatment A (reduced N dose), which differed significantly from treatments B, C, and F. Notably, no significant differences were observed in 2024 between treatments receiving the full nitrogen dose, regardless of the fertilizer form or struvite supplementation. In the 2025 season, the trend shifted as treatment A exhibited a statistically lower nitrogen content compared to all other fertilization variants. Regarding phosphorus (P), potassium (K), and sulphur (S), no statistically significant variances were detected in either year.

Table 19. Nutrient content in the dry matter of silage maize yield

| Treatment  | N      | P     | K     | S     |
|--|--------|-------|-------|-------|
|  | %      |       |       |       |
| <b>2024</b>  |        |       |       |       |
| A. 50% N (NH <sub>4</sub> NO <sub>3</sub> )                  | 0.79b  | 0.24a | 0.94a | 0.06a |
| B. 100% N (NH <sub>4</sub> NO <sub>3</sub> )                 | 1.09a  | 0.26a | 0.95a | 0.07a |
| C. 125% N (NH <sub>4</sub> NO <sub>3</sub> )                 | 1.13a  | 0.25a | 0.94a | 0.07a |
| D. 100% N (ASL)  | 1.07ab | 0.24a | 0.93a | 0.07a |
| E. 100% N (NH <sub>4</sub> NO <sub>3</sub> ) + P as struvite | 1.05ab | 0.26a | 0.95a | 0.07a |
| F. 100% N (ASL) + P as struvite                              | 1.13a  | 0.26a | 0.96a | 0.07a |
| <b>2025</b>  |        |       |       |       |
| A. 50% N (NH <sub>4</sub> NO <sub>3</sub> )                  | 1.01a  | 0.22a | 1.41a | 0.07a |
| B. 100% N (NH <sub>4</sub> NO <sub>3</sub> )                 | 1.32b  | 0.25a | 1.42a | 0.08a |
| C. 125% N (NH <sub>4</sub> NO <sub>3</sub> )                 | 1.46b  | 0.23a | 1.39a | 0.08a |
| D. 100% N (ASL)  | 1.24b  | 0.24a | 1.42a | 0.08a |
| E. 100% N (NH <sub>4</sub> NO <sub>3</sub> ) + P as struvite | 1.26b  | 0.23a | 1.41a | 0.08a |
| F. 100% N (ASL) + P as struvite                              | 1.25b  | 0.22a | 1.38a | 0.09a |

### Effects of the 'mineral' RNF on soil physical-chemical characteristics in seasons 2024 and 2025

During the 2024 growing season, statistically significant differences were confined to the soil content of phosphorus, potassium, and mineral nitrogen (Table 20). Treatment A exhibited significantly higher post-harvest concentrations of P and K compared to treatments characterized by higher nitrogen inputs or the application of alternative fertilizer forms, such as ASL and struvite. Regarding mineral nitrogen, the only statistically verified variance was the elevated N<sub>min</sub> level in [interreg-baltic.eu/project/cinurgi](https://interreg-baltic.eu/project/cinurgi)

treatment C relative to the other experimental variants. No significant effects were observed for soil pH, sulphur, organic carbon, or phosphorus determined by the Melich 3 method.

In the 2025 season, the influence of the various fertilization regimes on the chemical properties of the soil was negligible, as no statistically significant differences were detected across any of the analyzed parameters, with all results classified within a single homogeneous group (Table 20).

**Table 20. Nutrient content in the soil before sowing and after harvesting maize**

| Treatment            |  | pH   | P<br>(Egner-Rhiem) | P<br>(Melich 3) | K <sub>2</sub> O | S     | Nmin  | Corg  |
|----------------------|--|------|--------------------|-----------------|------------------|-------|-------|-------|
|                      |  |      | mg/100g of soil    |                 |                  |       |       |       |
| <b>2024</b>          |  |      |                    |                 |                  |       |       |       |
| <b>Before sowing</b> |  | 5.2  | 15.8               | 19.1            | 17.5             | 0.28  | 4.0   | 0.77  |
| <b>After harvest</b> | A<br>50% N (NH <sub>4</sub> NO <sub>3</sub> )                    | 5.6a | 16.7b              | 20.7a           | 18.1b            | 0.33a | 3.4a  | 0.78a |
|                      | B<br>100% N (NH <sub>4</sub> NO <sub>3</sub> )                   | 5.4a | 14.7ab             | 20.6a           | 16.2ab           | 0.26a | 4.7a  | 0.75a |
|                      | C<br>125% N (NH <sub>4</sub> NO <sub>3</sub> )                   | 5.2a | 13.4a              | 17.7a           | 15.8a            | 0.26a | 7.2b  | 0.74a |
|                      | D<br>100% N (ASL)  | 5.0a | 13.2a              | 18.3a           | 15.2a            | 0.35a | 3.5a  | 0.70a |
|                      | E<br>100% N (NH <sub>4</sub> NO <sub>3</sub> ), P<br>as strivite | 5.0a | 13.1a              | 18.6a           | 14.9a            | 0.30a | 4.2a  | 0.70a |
|                      | F<br>100% N (ASL),<br>P as strivite                              | 5.0a | 13.1b              | 18.4a           | 15.4a            | 0.31a | 3.5a  | 0.73a |
| <b>2025</b>          |  |      |                    |                 |                  |       |       |       |
| <b>Before sowing</b> |  | 5.4  | 17.1               | 19.9            | 12.9             | 0.40  | 15.1  | 1.42  |
| <b>After harvest</b> | A<br>50% N (NH <sub>4</sub> NO <sub>3</sub> )                    | 5.7a | 19.7a              | 22.3a           | 15.4a            | 0.45a | 18.3a | 1.64a |
|                      | B<br>100% N (NH <sub>4</sub> NO <sub>3</sub> )                   | 5.6a | 18.6a              | 18.9a           | 14.3a            | 0.40a | 17.1a | 1.60a |
|                      | C<br>125% N (NH <sub>4</sub> NO <sub>3</sub> )                   | 5.4a | 18.9a              | 22.8a           | 14.8a            | 0.44a | 19.9a | 1.61a |
|                      | D<br>100% N (ASL)  | 5.4a | 17.7a              | 20.5a           | 13.9a            | 0.51a | 20.8a | 1.54a |
|                      | E<br>100% N (NH <sub>4</sub> NO <sub>3</sub> ), P<br>as strivite | 5.5a | 16.2a              | 19.7a           | 14.5a            | 0.43a | 18.4a | 1.57a |
|                      | F<br>100% N (ASL),<br>P as strivite                              | 5.3a | 15.9a              | 20.2a           | 13.2a            | 0.49a | 17.6a | 1.56a |

## 'Organic' RNF

### Maize

#### Biomass accumulation and SPAD measurements during vegetation

In both seasons (2024–2025), the dynamics of maize dry matter accumulation showed no statistically significant differentiation during the initial vegetative phase (Term 1) (Fig. 24 - 25). In the 2024 season, at the second node stage (Term 2), a statistically significant increase in biomass was observed in the fertilized treatments compared to the control, with the Planteo pellet variant demonstrating the highest production efficiency. By the final measurement stage (Term 3), the differences between the fertilization groups and the control became statistically non-significant, although the Planteo pellet treatment consistently maintained numerically higher biomass productivity. A similar trend was observed in 2025, where, despite the absence of statistically proven differences, the application of organic and mineral fertilizers stimulated steady plant growth compared to the zero-nitrogen control.

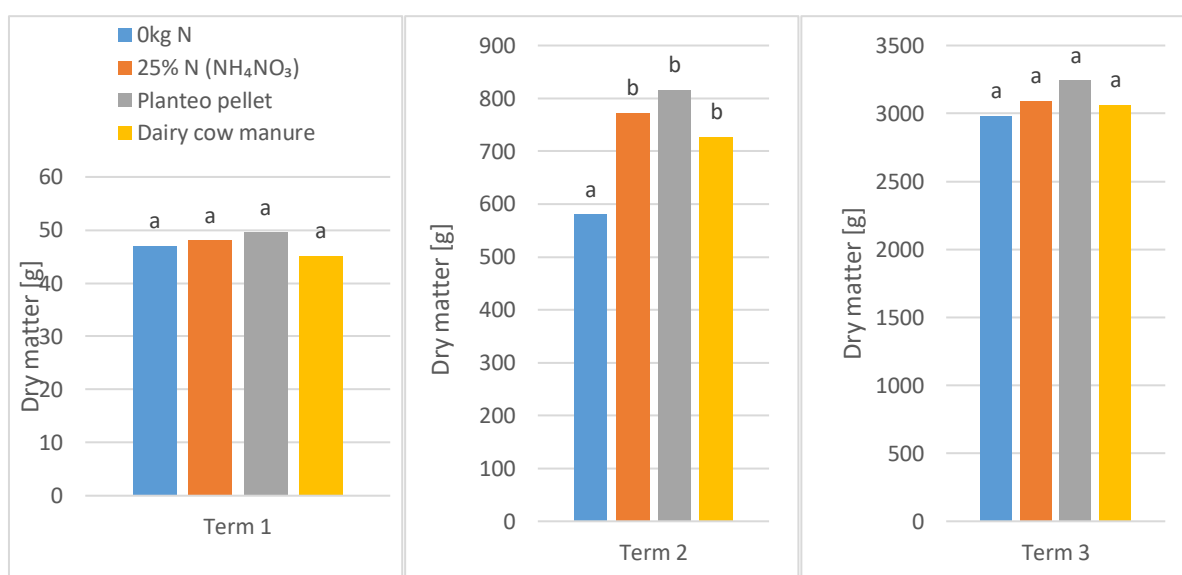


Figure 24. Maize biomass accumulation during vegetation (5-6th leaf stage (BBCH 15-16), 2nd node stage (BBCH 32) and tasselling stage (BBCH 53-55)) in the 2024 season.

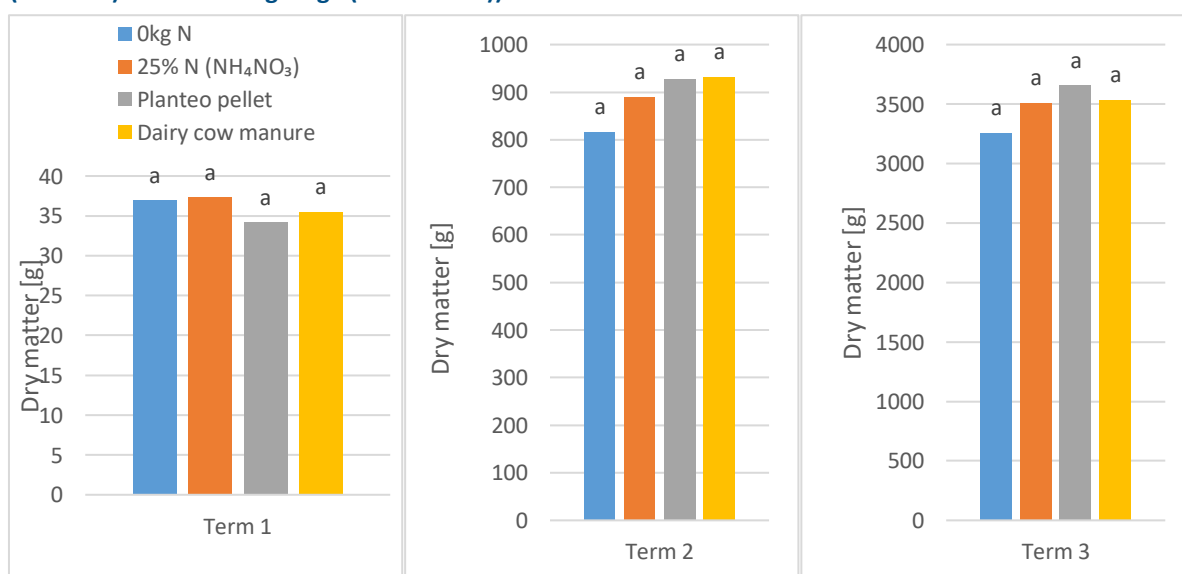
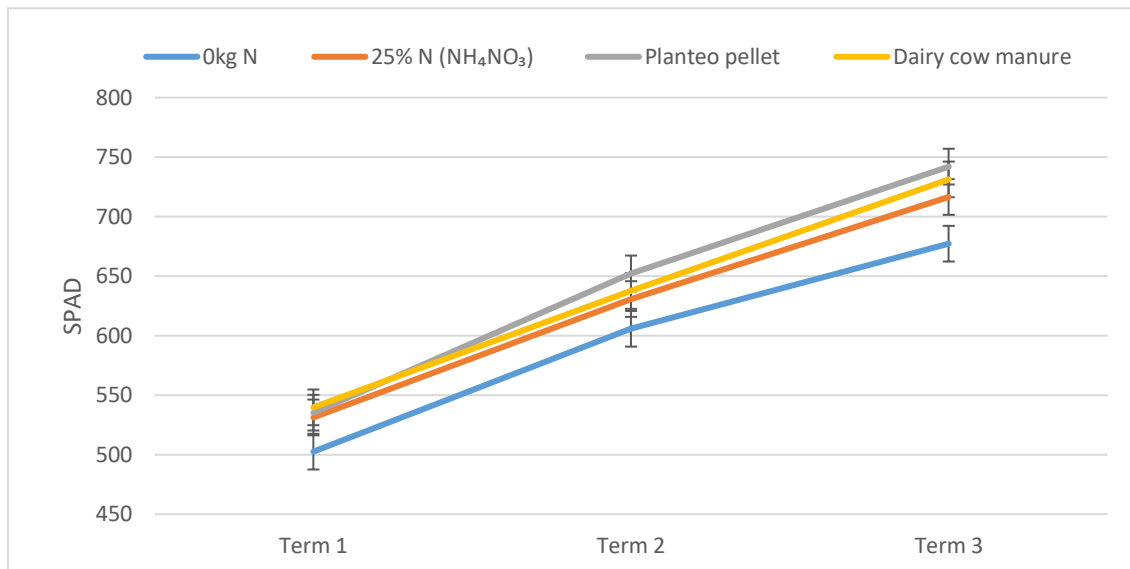
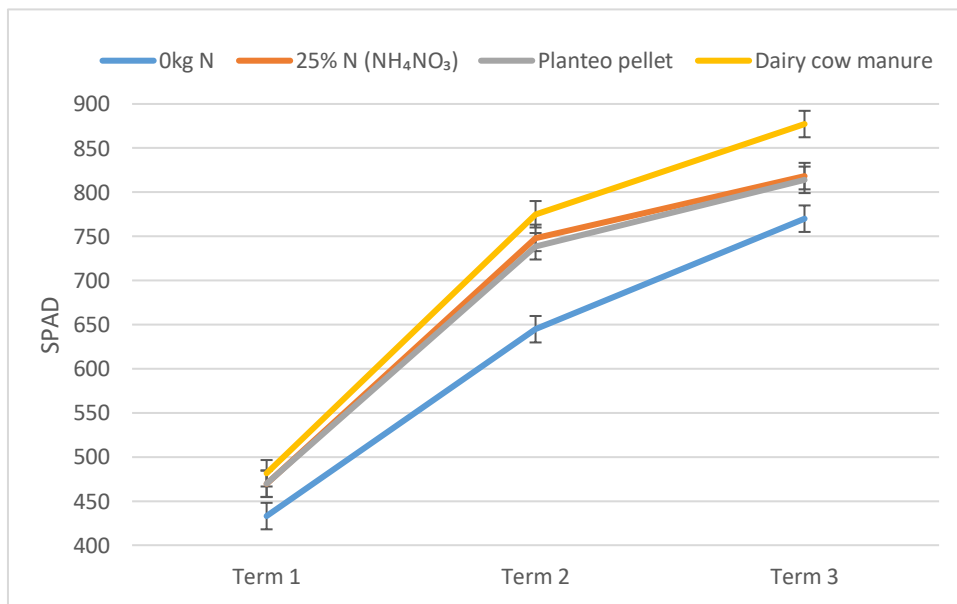


Figure 25. Maize biomass accumulation during vegetation (5-6th leaf stage (BBCH 15-16), 2nd node stage (BBCH 32) and tasselling stage (BBCH 53-55)) in the 2025 season.

In both analyzed years (2024 and 2025), a clear upward trend in the SPAD index was observed throughout maize development, with all fertilized treatments significantly outperforming the unfertilized control (0 kg N) (Fig. 26 - 27). In the 2024 season, the highest values were recorded in the Planteo pellet treatment, while in 2025, dairy cow manure provided the best results in terms of plant nitrogen nutrition. The leaf chlorophyll content, expressed as the SPAD index, following the application of organic fertilizers is comparable to the treatment with nitrogen fertilization at 25% of the optimal dose.



**Figure 26.** Index SPAD measured in maize during vegetation (5-6th leaf stage (BBCH 15-16), 2nd node stage (BBCH 32) and tasselling stage (BBCH 53-55)) in the 2024 season.



**Figure 27.** Index SPAD measured in maize during vegetation (5-6th leaf stage (BBCH 15-16), 2nd node stage (BBCH 32) and tasselling stage (BBCH 53-55)) in the 2025 season.

### Silage dry matter yield

The highest maize silage dry matter yield in 2024 was obtained in the variant where Planteo pellets were applied (Fig. 28). It significantly exceeded the yield from the non-nitrogen-fertilized treatment and was comparable to the results from manure fertilization and the 25% reduced nitrogen dose. In 2025, mineral fertilization resulted in the highest yield, significantly surpassing the zero-

nitrogen control. However, the yields from nitrogen fertilization, Planteo pellets, and manure were statistically similar.

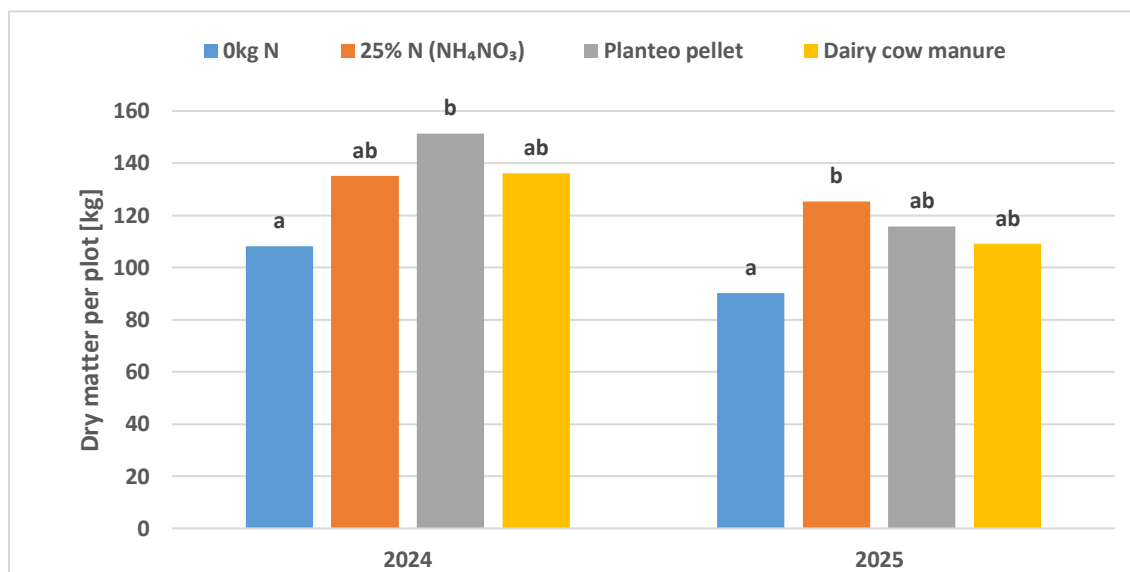


Figure 28. Dry matter yield of maize silage from a 60 m<sup>2</sup> plot.

### Nutrient content in the yield

In 2024, significant differences were observed across all analyzed elements. The highest nitrogen concentration was recorded in plants treated with Planteo pellet (0.72%), which was higher compared to all other treatments (control, mineral fertilization, and dairy cow manure), where values ranged from 0.61% to 0.63% (Table 21). A similar trend was observed for phosphorus (P); the application of organic fertilizers—Planteo pellet and dairy cow manure—resulted in a higher phosphorus content (0.32% and 0.30%, respectively) compared to the control and mineral nitrogen treatments. Regarding potassium in 2024, an inverse relationship was observed. The highest concentrations were found in the control (2.40%) and mineral fertilization (2.24%) plots. The use of organic fertilization (Planteo pellet and manure) led to a significant decrease in potassium concentration, dropping to 1.70%.

In 2025, the impact of fertilization on the chemical composition of the plants was less pronounced regarding nitrogen and phosphorus (Table 21). No statistically significant differences were found between the treatments for N and P concentrations during this period. However, the year confirmed the established trend for potassium. Consistent with the previous year, plants from the control and mineral nitrogen plots exhibited significantly higher K content (1.36% and 1.45%, respectively) compared to those treated with Planteo pellet and dairy cow manure (1.15–1.16%).

Table 21. Nutrient content in the dry matter of silage maize yield

| Treatment                                | N     | P     | K     |
|--|-------|-------|-------|
|  | %     |       |       |
| <b>2024</b>                              |       |       |       |
| 0kg N                                    | 0.62a | 0.29a | 2.40b |
| 25% N (NH <sub>4</sub> NO <sub>3</sub> ) | 0.61a | 0.26a | 2.24b |
| Planteo pellet                           | 0.72b | 0.32b | 1.70a |
| Dairy cow manure                         | 0.63a | 0.30b | 1.70a |
| <b>2025</b>                              |       |       |       |
| 0kg N                                    | 1.08a | 0.20a | 1.36b |
| 25% N (NH <sub>4</sub> NO <sub>3</sub> ) | 1.05a | 0.20a | 1.45b |
| Planteo pellet                           | 0.99a | 0.21a | 1.16a |
| Dairy cow manure                         | 1.11a | 0.22a | 1.15a |

## Effects of the 'organic' RNF on soil physical-chemical characteristics in seasons 2024 and 2025

In the 2024 growing season, statistically significant differences were observed only regarding soil phosphorus content (both analytical methods) and potassium (Table 22). Treatment C (Planteo pellet) exhibited significantly higher post-harvest concentrations of these nutrients compared to the other experimental variants, including the control and dairy cow manure. No significant effects were detected for soil pH, mineral nitrogen, or organic carbon content. In the 2025 season, the impact of the applied fertilization on soil chemical properties was statistically non-significant across all analyzed parameters (Table 22).

**Table 22. Nutrient content in the soil before sowing and after harvesting maize**

| Treatment            |   | pH   | P<br>(Egner-Rhiem) | P<br>(Melich 3) | K <sub>2</sub> O | Nmin  | Corg  |
|----------------------|---|------|--------------------|-----------------|------------------|-------|-------|
|                      |   |      | mg/100g of soil    |                 |                  |       |       |
| <b>2024</b>          |   |      |                    |                 |                  |       |       |
| <b>Before sowing</b> |   | 5.2  | 15.8               | 19.1            | 17.5             | 4.01  | 0.77  |
| <b>After harvest</b> | A<br>0kg N                                    | 5.7a | 17.9a              | 23.5a           | 19.2a            | 3.22a | 0.79a |
|                      | B<br>25% N (NH <sub>4</sub> NO <sub>3</sub> ) | 5.6a | 18.9a              | 26.1a           | 18.4a            | 4.05a | 0.76a |
|                      | C<br>Planteo pellet                           | 5.7a | 24.3b              | 30.1b           | 21.5b            | 3.60a | 0.79a |
|                      | D<br>Dairy cow manure                         | 5.5a | 15.1a              | 25.1a           | 17.8a            | 3.93a | 0.79a |
| <b>2025</b>          |   |      |                    |                 |                  |       |       |
| <b>Before sowing</b> |   | 5.4  | 17.1               | 19.9            | 12.9             | 15.1  | 1.42  |
| <b>After harvest</b> | A<br>0kg N                                    | 5.9a | 19.1a              | 20.5a           | 13.8a            | 13.8a | 1.22a |
|                      | B<br>25% N (NH <sub>4</sub> NO <sub>3</sub> ) | 5.6a | 18.7a              | 20.4a           | 14.8a            | 16.5a | 1.16a |
|                      | C<br>Planteo pellet                           | 5.5a | 18.2a              | 19.7a           | 14.3a            | 13.3a | 1.38a |
|                      | D<br>Dairy cow manure                         | 5.7a | 17.9a              | 19.2a           | 14.1a            | 12.2a | 1.21a |

## Effects of the 'organic' RNF on microbiological activity in soil after maize harvest in seasons 2024 and 2025

The analysis shows that the influence of the tested treatments on soil microbiological activity was not fully consistent across the two study years, and the pattern of significant differences varied depending on the enzyme and the growing season (Table 23). In 2024, dehydrogenase activity did not differ significantly among treatments, whereas in 2025, clear differentiation appeared, with the highest activity observed in the Planteo pellet treatment. For acid phosphatases, significant differences were present in both years, but the grouping of treatments differed, indicating a lack of stable, repeatable effects. A similar pattern was observed for alkaline phosphatases: although significant differences occurred in both seasons, different treatments formed the highest-activity groups in each year.

**Table 23. Microbiological activity in soil after maize harvest**

| Treatment                                | Dehydrogenases         | Acid phosphates       | Alkaline phosphates |
|--|------------------------|-----------------------|---------------------|
|  | ug TPF/g d.m. soil/24h | ug PNP/g d.m. soil /h |                     |
| <b>2024</b>                              |                        |                       |                     |
| 0kg N                                    | 25.52a                 | 52.82b                | 23.12c              |
| 25% N (NH <sub>4</sub> NO <sub>3</sub> ) | 26.46a                 | 50.37a                | 21.89bc             |
| Planteo pellet                           | 26.69a                 | 50.40a                | 20.52b              |
| Dairy cow manure                         | 26.99a                 | 53.53b                | 18.35a              |
| <b>2025</b>                              |                        |                       |                     |
| 0kg N                                    | 96.18bc                | 106.48c               | 23.84b              |
| 25% N (NH <sub>4</sub> NO <sub>3</sub> ) | 92.45b                 | 104.42bc              | 19.19a              |
| Planteo pellet                           | 102.80c                | 90.75a                | 24.99b              |
| Dairy cow manure                         | 82.10s                 | 97.33ab               | 20.17a              |

### Soil organic matter fractions

The use of different fertilization methods influenced the diversification of the quantitative and qualitative characteristics of soil organic matter (Table 24). Nitrogen mineral fertilization (object B) caused a much greater impact on organic matter transformations than organic fertilization (objects C and D). This effect was particularly observed in the variable concentration of humic acids. The addition of nitrogen caused a decrease in the humification index (HA:FA), which indicates a greater susceptibility of organic matter to degradation as a result of the mineralization processes.

Low ratio of humic acids to fulvic acids, with their simultaneous high proportion compared to humins in soils with organic fertilizers amendments, indicates the stabilization of organic matter. Organic fertilization caused a significant decrease in the content of labile forms of organic matter (fulvic and humic acids) as a result of the ongoing processes of its humification, initiating an increase in the total content of the most stable humin fraction. This process is confirmed by a significantly lower depolymerization index ((HA+FA)/HUM), indicating the formation of strong organic-mineral bonds resistant to decomposition. These processes are the result of high biological activity of the soil, which influences the formation of permanent organic matter structures resistant to degradation. At the same time, they affect the higher availability of low-polymer humic acids responsible for the migration of nutrients from the soil to the plant. Additionally, the results indicate that better effects were obtained by using pellet from digestate in a much lower dose than dairy cow manure.

**Table 24. Content of humic substances in the soil after maize harvest**

| Treatment                                   | Fulvic acids (FA) | Humic acids (HA) | Humins (HUM) | Humification index (HA:FA) | Depolymerization index ((HA+FA)/HUM) |
|---|-------------------|------------------|--------------|----------------------------|--------------------------------------|
|   | g/kg              |                  |              |                            |                                      |
| <b>2024</b>                                 |                   |                  |              |                            |                                      |
| A. 0kg N                                    | 1.09              | 4.44             | 3.68         | 4.07                       | 1.37                                 |
| B. 25% N (NH <sub>4</sub> NO <sub>3</sub> ) | 0.98              | 3.68             | 3.58         | 3.71                       | 1.29                                 |
| C. Planteo pellet                           | 1.08              | 1.95             | 6.04         | 1.81                       | 0.75                                 |
| D. Dairy cow manure                         | 1.06              | 1.76             | 5.67         | 1.66                       | 0.77                                 |
| <b>2025</b>                                 |                   |                  |              |                            |                                      |
| A. 0kg N                                    | 1.84              | 2.83             | 6.4          | 1.54                       | 0.74                                 |
| B. 25% N (NH <sub>4</sub> NO <sub>3</sub> ) | 1.83              | 2.67             | 5.67         | 1.47                       | 0.80                                 |
| C. Planteo pellet                           | 2.04              | 2.37             | 6.35         | 1.17                       | 0.69                                 |
| D. Dairy cow manure                         | 2.00              | 2.05             | 5.99         | 1.03                       | 0.68                                 |

### 3.2.4. Conclusions

#### 2024

In the 2024 season, the growth dynamics of spring wheat and maize indicated that the primary factor differentiating plant development was the nitrogen fertilization rate, while the form of nitrogen applied did not significantly affect biomass accumulation. In spring wheat, biomass accumulated at a similar level across all fertilization treatments, and SPAD values remained stable, confirming a comparable level of nitrogen nutrition. Only reducing the nitrogen dose to 50% led to a clear decrease in SPAD, whereas the full and increased nitrogen doses maintained the index at a similar level. Grain yield of spring wheat remained stable in treatments receiving the full nitrogen dose, regardless of the form of nitrogen used or struvite addition, and increasing the dose to 125% did not provide additional yield benefits.

In maize, biomass accumulation in 2024 differed only at the later growth stage, where the increased nitrogen dose (125% N) resulted in higher biomass production compared with the reduced dose. SPAD values confirmed this pattern — only the 50% N treatment showed significantly lower values, while the nitrogen form did not differentiate plant nitrogen status. Maize silage dry matter yield increased significantly with nitrogen rates up to 100% N, while further increases did not result in additional yield gains.

The mineral fertilizer replacement value of ASL in 2024 was high in both wheat and maize (95.7% and 98.5%, respectively), confirming its very good effectiveness under field conditions and its suitability as a full-value nitrogen source in fertilization systems.

The chemical composition of the yield in 2024 responded mainly to the nitrogen fertilization level. In spring wheat, significant differences were observed only for nitrogen content, while P, K and S remained stable. In maize, the lowest nitrogen concentrations were recorded in the 50% N treatment, while the remaining variants did not differ from each other. Phosphorus and sulphur contents remained stable, whereas potassium content was clearly lower in treatment with organic fertilizers.

The physicochemical properties of the soil after harvesting spring wheat and maize in 2024 showed only minor differences. In wheat, significantly higher sulphur concentrations were recorded in ASL-fertilized treatments, while other parameters remained stable. In maize, differences were mainly related to phosphorus, potassium and mineral nitrogen, with the highest P and K<sub>2</sub>O values recorded in the 50% N treatment and the highest N<sub>min</sub> level in the 125% N treatment. Application of struvite has no negative effect on the P level in soil.

For organic fertilizers, the 2024 results confirmed their beneficial effect on maize development and soil properties. Maize biomass in the Planteo pellet treatments was higher than in the control, and SPAD values remained comparable to mineral fertilization. Silage yield in organically fertilized treatments (Planteo pellets and manure) was similar to yields obtained under mineral fertilization, confirming their suitability in fertilization systems with reduced mineral nitrogen input. The chemical composition of maize fertilized organically was characterized by higher nitrogen and phosphorus content and lower potassium content compared with mineral fertilization.

Regarding soil properties, organic fertilizers promoted an increase in phosphorus and potassium content and contributed to the positive effect on soil organic matter through an increased share of humic fractions. At the same time, soil microbiological activity in 2024 varied among treatments, but without a clear, repeatable pattern, confirming the complex soil response to organic fertilization.

## 2025

In the 2025 season, the growth of winter wheat and maize was primarily determined by the nitrogen fertilization rate, while the form of nitrogen applied did not significantly affect biomass accumulation or SPAD values. In winter wheat, biomass accumulated at a similar level across all treatments receiving the full nitrogen dose, and reducing the dose to 50% resulted only in a decrease in SPAD at later growth stages. Grain yield remained stable in treatments receiving 100% N, regardless of nitrogen form or struvite addition, while reducing the dose led to a clear yield decrease. In maize, full and increased nitrogen doses ensured higher biomass accumulation and higher SPAD values than the reduced dose, while the nitrogen form did not differentiate plant nitrogen status. Similarly to 2024, dry matter yield increased significantly only with nitrogen rates up to 100% N.

The mineral fertilizer replacement value of ASL was high in both wheat and maize, reaching 97.1% and 105.7%, respectively, confirming the strong field performance of this fertilizer. The chemical composition of the yield in 2025 responded only to the nitrogen fertilization level — the lowest nitrogen concentrations were recorded in the 50% N treatments, while P, K and S contents remained stable and did not differ significantly among treatments.

The physicochemical properties of the soil after harvesting winter wheat and maize in 2025 showed no significant differences among fertilization treatments. All analyzed parameters, including pH, phosphorus, potassium, sulphur, mineral nitrogen and organic carbon, remained within a single homogeneous group, indicating no short-term effect of applied RNFs on soil condition.

For organic fertilizers, the 2025 results confirmed their beneficial, although not fully consistent, influence on maize development and soil properties. Maize biomass in the Planteo pellet and manure treatments was higher than in the control, and SPAD values remained comparable to mineral fertilization at the 25% N dose. Silage yields in organically fertilized treatments were similar to those obtained under mineral fertilization. The chemical composition of maize fertilized organically was characterized by lower potassium content, while nitrogen and phosphorus contents remained comparable to mineral fertilization.

Regarding soil properties, organic fertilizers positively influence soil organic matter through an increased share of humin fractions and a lower depolymerization index, indicating the formation of [interreg-baltic.eu/project/cinurgi](https://interreg-baltic.eu/project/cinurgi)

more stable organo-mineral structures resistant to decomposition. At the same time, soil microbiological activity in 2025 varied among treatments without a repeatable pattern, confirming the seasonal variability of soil responses to organic fertilization.

Overall, the two-year study confirmed that 'mineral' Recycled Nutrient Fertilizers (ASL and struvite) demonstrate high agronomic efficiency, comparable to conventional mineral fertilizers in wheat and maize cultivation. The use of RNFs and organic fertilizers maintained stable macronutrient content in the crop dry matter. The application of 'organic' RNFs (e.g., Planteo pellets) showed a yield effect similar to that of manure. Furthermore, it positively influenced the quality of soil organic matter by increasing the proportion of humic fractions and lowering the depolymerization index, which indicates the formation of stable organo-mineral structures.

### 3.3. Sweden

#### 3.3.1 Methodology

##### Field site

The two experiments were conducted at Lanna research station in southwest Sweden (58°20'46.0"N 13°07'23.9"E) during 2024-2025. The long-term mean annual precipitation at the site is 584 mm, and the mean annual temperature is 7.3°C (SMHI, 1991–2020). The soil at Lanna is a Udic Haploboroll according to the USDA classification system, with 40-45 % clay content (particle size <0.002 mm) in the topsoil (0–30 cm depth) and up to 60% in the subsoil. The top-soil had a low content of plant-available phosphorus (P) (1-3 mg/100 g in 2024, and 1.6 mg/100 g in 2025, P-AL class I-II), which was the most important selection criteria for this study. The subsoil had a moderate P content (4-8 mg/100 g, P-AL class III). The Soil P content was determined by extraction with ammonium-lactate at pH 3.75 and analyzed with ICP-OES (SS 028310:1993, modified) as ammonium-lactate soluble P (P-AL), which is the common method in Sweden for the determination of the amount of plant-available P in the soil.

##### Experimental design, fertilizers and treatments

The aim of the study was to assess the effects of different recycled nutrient fertilisers (RNFs) in relation to conventional mineral P fertilizer (triple super phosphate, TSF). The RNFs used in the experiment were of different origins (Table 25).

**Table 25. Content of total nitrogen (N), phosphorus (P) and carbon (C) in the different RNFs as % of dry matter. Total C contents were only determined for the biochars. Ammonium nitrate (N-NH<sub>4</sub>) contents were only determined in 2025**

| Year | Treatment                 | Original material                             | P (%) | N (%) | N-NH <sub>4</sub> , g/kg | C (%) |
|------|---------------------------|---|-------|-------|--------------------------|-------|
| 2024 | Compost <sub>dig</sub>    | Digested manure                               | 1.7   | 3.7   |                          |       |
|      | MBM <sub>pellet</sub>     | Meat and bone powder                          | 2.1   | 8.8   |                          |       |
|      | Biochar <sub>slraw</sub>  | Raw sewage sludge                             | 5.9   | 2.9   |                          | 29    |
|      | Biochar <sub>sldig</sub>  | Digested sewage sludge                        | 5.6   | 2.8   |                          | 27    |
|      | Biochar <sub>plant</sub>  | Plant residues                                | 5.3   | 2.5   |                          | 72    |
| 2025 | Struvite (ST)             | Sewage sludge                                 | 10.3  | 25.4  | 1.14                     |       |
|      | Pelletized digestate (PD) | Digested pig manure and house slaughter waste | 0.91  | 64.2  | 53.6                     |       |

##### Experiment 2024

Compost, pellets and three types of biochar were used in the study. Compost<sub>dig</sub> was obtained from the demonstration project Circular NP, where digested manure was separated into a solid phase, in which P was accumulated. This raw solid phase was then composted through biothermal drying to produce a drier (90% dry matter), transportable, P-rich fertilizer with low N content. It was tested for the first time in this study (Table 25). The MBM pellet is a pelletized fertilizer available on the Swedish market and is commonly used in organic farming. It is based on pulverized bones and meat from slaughter waste and has an N:P:K ratio of 9:2:5. Three biochars of different origins were also included: two derived from wastewater treatment plants in Sweden (one from raw sewage sludge (biochar<sub>slraw</sub>) and one from digested sewage sludge (biochar<sub>sldig</sub>) and one produced from residues of a seed-producing company (biochar<sub>plant</sub>). The biochars are mainly marketed as soil improvers.

The experiment included a control treatment without P (0P) and two mineral P treatments: 8 kg P/ha (1P) and 16 kg P/ha (2P). This stepwise increase in mineral P applications (0P, 1P and 2P) was

used to assess the agronomic use efficiency of the RNFs. RNFs were applied at a uniform rate of 16 kg P/ha, corresponding to application rates of 940 kg/ha for compostdig, 760 kg/ha for MBM pellet, and 270-300 kg/ha for the biochars application. The treatments were applied in 3 x 12m plots using a complete randomized design with four replicates (Table 26). Nitrogen, potassium and sulphur were applied in excessive amounts in order to avoid limiting crop yield. The differences in grain yields and content of N and P in grain between treatments were statistically evaluated with ANOVA and the Tukey test.

### Experiment 2025

The experiment included nine treatments designed to compare the effectiveness of two RNF (struvite and pelletized digestate) with a conventional mineral P fertilizer (TSP). Struvite (ST) was supplied by the CiNURGi partner SoepenberGmbH (Germany) and produced through precipitation from sewage sludge. The pelletized digestate (PD) was produced in Sweden (Alvilsgården) from digested pig manure and slaughterhouse by-products (Table 25).

Two P application rates were tested for each fertilizer type: 7 kg P/ha (half dose) and 14 kg P/ha (full dose). These corresponded to application rates of 68 kg/ha and 136 kg/ha for struvite, 770 kg/ha and 1.54 t/ha for pelletized digestate, and 35 kg/ha and 70 kg/ha for TSP. All RNF treatments received a total nitrogen input of 120 kg N/ha, calculated by accounting for the ammonium-N supplied with the RNF and supplementing the remainder with mineral N fertilizer (ammonium nitrate).

In addition to the fertilized treatments, the design included three reference treatments to separate the effects of P and N fertilization from background soil fertility: an unfertilized control (PON0) with no added P or N, a treatment receiving only mineral N (PON1, 120 kg N/ha) to assess crop response to N under P deficiency, and a treatment receiving only P (NOP2, 14 kg P/ha as TSP) to evaluate crop response to P in the absence of N. Potassium and sulphur were applied in excess across all treatments to avoid nutrient limitations. The treatments were applied in 1.7 x 12m plots using a complete randomized design with four replicates. The differences in obtained results between treatments were statistically evaluated with ANOVA and the Tukey test.

**Table 26. Experimental treatments**

| Treatment                | Fertilizer type                          | Application P rate, ha | Mineral Fertilizer         |
|--------------------------|--|------------------------|----------------------------|
| 2024                     |  |                        |                            |
| OP                       |  |                        | No added P, NKS, excess    |
| 1P                       | Triple super phosphate                   | 8 kg P                 | Min-P 8 kg + NKS, excess   |
| 2P                       | Triple super phosphate                   | 16 kg P                | Min-P 16 kg + NKS, excess  |
| Compost <sub>dig</sub>   | Separated digestate (solid), Circular NP | 16 kg P                | Min-NKS, excess            |
| MBM <sub>pellet</sub>    | Pellets of bone and meat, Biofer raps    | 16 kg P                | Min-NKS, excess            |
| Biochar <sub>slraw</sub> | Biochar from raw sewage sludge           | 16 kg P                | Min-NKS, excess            |
| Biochar <sub>sldig</sub> | Biochar from digested sewage sludge      | 16 kg P                | Min-NKS, excess            |
| Biochar <sub>plant</sub> | Biochar from plant residues, Skånefrö    | 16 kg P                | Min-NKS, excess            |
| 2025                     |  |                        |                            |
| P0N0                     |  |                        | No added P, N + KS, excess |
| P0N1                     |  |                        | Min-N 120 kg + KS, excess  |
| P1N1                     | Triple super phosphate                   | 7 kg P                 | Min-N 120 kg + KS, excess  |
| P2N1                     | Triple super phosphate                   | 14 kg P                | Min-N120 kg + KS, excess   |
| ST1                      | Struvite, Soepenber                      | 7 kg P                 | Min-N 120 kg + KS, excess  |
| ST2                      | Struvite, Soepenber                      | 14 kg P                | Min-N 120 kg + KS, excess  |
| PD1                      | Pelletized digestate, Alviksgården       | 7 kg P                 | Min-N 120 kg+ KS, excess   |
| PD2                      | Pelletized digestate, Alviksgården       | 14 kg P                | Min-N 120 kg +KS, excess   |
| NOP2                     | Triple super phosphate                   | 14 kg P                | KS, excess                 |

## Crop management and sampling

### Experiment 2024

Oats were used as the study crop and were sown on May 13, the same day the fertilizers were applied. The sowing date was later than normal for the region, partly due to a cold spring that lasted until early May (Figure 1) and partly due to delays in production of RNF, specifically the compost from the Circular NP project. The TSP and the MBM pellets were applied using a combi-drill, while biochars and compostdig were spread manually and incorporated into the soil to a depth of 5 cm before sowing. Mineral N was applied at sowing, aiming at a rate of 90 kg/ha in all treatments. The application rate of mineral N fertilizer was adjusted based on the N content and availability in the RNFs. Additional mineral N (27 kg/ha) was applied on May 22, in all treatments.

The crop was harvested on August 31 with a combine, with the determination of grain yield in all plots. Samples of grain were taken for measurements of dry matter, N and P content.

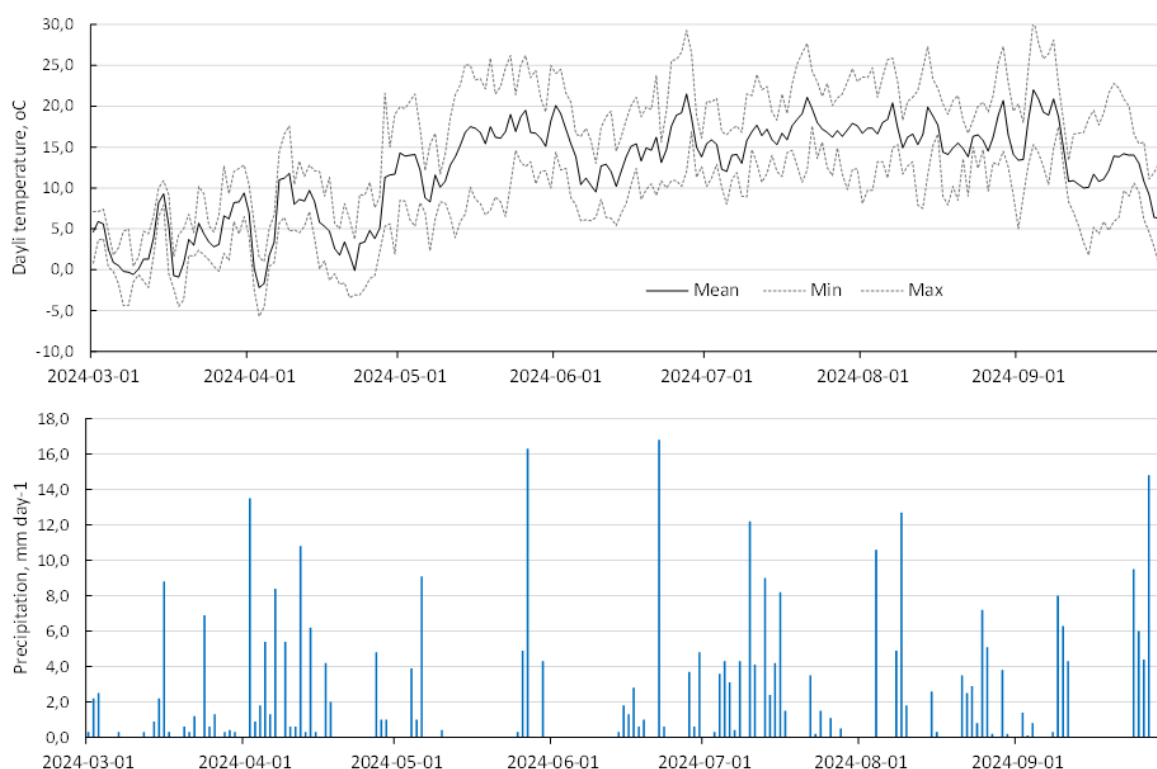
### Experiment 2025

Spring barley, which has a higher P demand than oats used in 2024, was selected for the 2025 experiment. Sowing took place on 31 March, and all RNF and TSP fertilizers were applied with a combi-drill. Mineral N was applied using a combination of placement with the combi-drill and additional surface application to reach the target rate of 120 kg N/ha in all N-fertilized treatments. For the struvite treatments (ST1 and ST2), 0.333 t/ha of N was applied with the combi-drill, supplemented with 0.111 t/ha. For the pelletized digestate treatments, PD1 received 0.180 t/ha with the combi-drill and 0.111 t/ha as an additional application, whereas PD2 received no N with the combi-drill and 0.139 t/ha as an additional application. All remaining treatments receiving TSP were supplied with 0.333 t/ha of N with the combi-drill and 0.111 t/ha as an additional application. The

crop was harvested on 16 July, following the same schedule as in 2024. Grain samples were collected for analysis of dry matter, N and P concentrations. In addition, topsoil samples were taken to determine soil mineral N, pH, P-AL, K-AL as well as other macro and micronutrients.

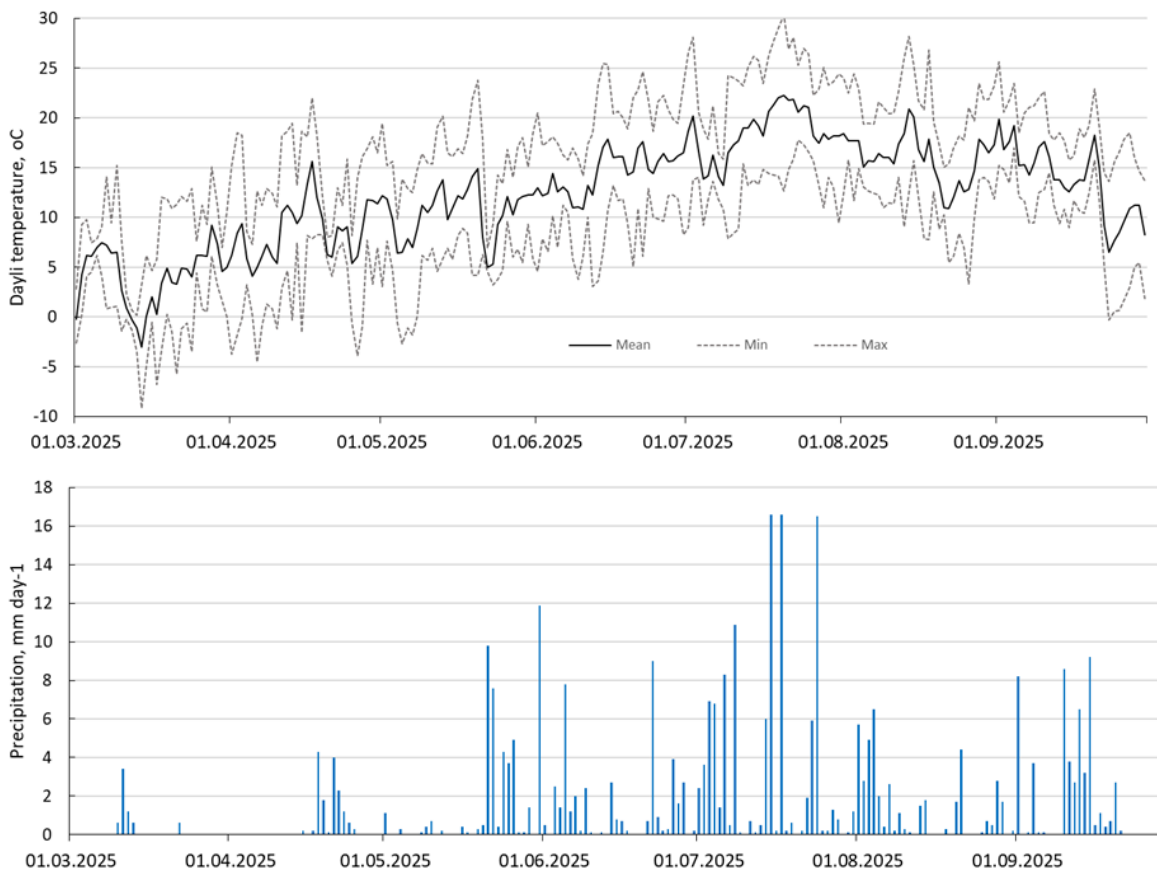
### 3.3.2 Weather conditions

Daily mean, minimum and maximum temperatures, and daily precipitation from March 2024 until September are presented in Figure 29. The spring was colder than what is common for the region and this contributed to a time of sowing of the oat crop which was approximately two weeks later (13th of May) than expected late sowing of the oat crop (13th of May). Besides this, the cropping season was good, and the oats developed very well. During the crop growing season until the end of August, the total amount of precipitation was 184 mm, with the distribution presented in Figure 29.



**Figure 29. Weather data for the period March to September 2024. The crop was sown on the 13th of May and harvested on the 31st of August. a. Daily mean, minimum and maximum temperatures (°C); b. Daily precipitation (mm)**

Spring conditions in 2025 were generally favourable for sowing and crop emergence (Fig. 30). The absence of heavy rainfall allowed timely field operations, and soil moisture levels were adequate for germination. Air temperatures increased gradually through the spring, and together with sufficient rainfall, supported full development of the spring barley crop.

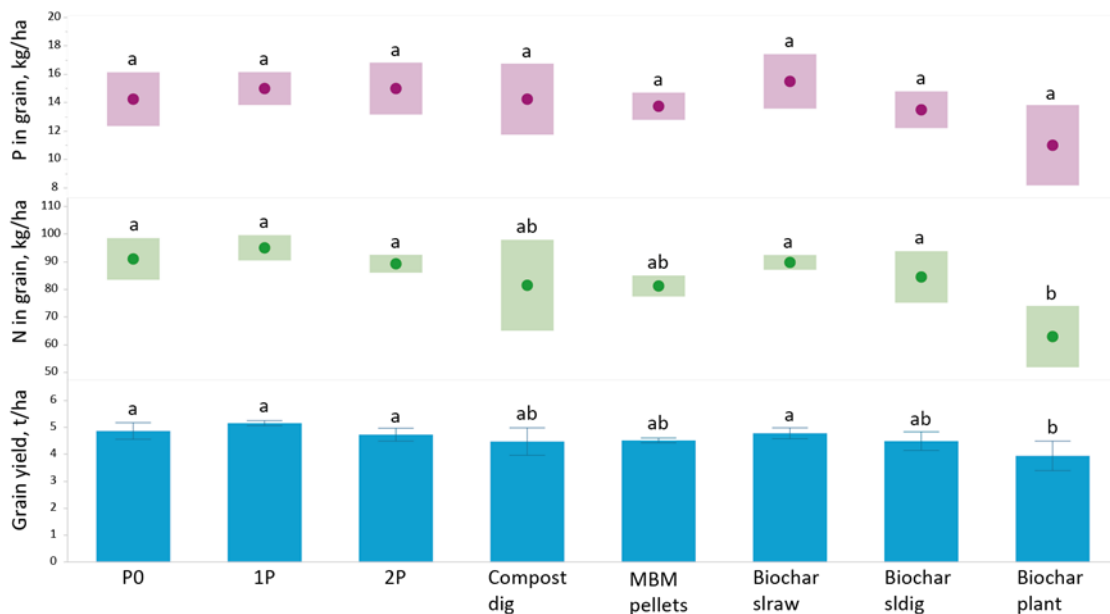


**Figure 30. Weather data for the period March to September 2025. The crop was sown on the 31st of March and harvested on the 16th of July. a. Daily mean, minimum and maximum temperatures (°C); b. Daily precipitation (mm)**

### 3.3.3 Results

#### Experiment 2024

The oat crop developed very well, and grain yields were on average 4600 t/ha, which was considered satisfactory (Fig. 31). The average N and P concentrations in the grain were 1.82 % and 0.30 %, respectively, implying that 84 kg N/ha and 14 kg P/ha were removed with harvested grain. The grain yields did not differ significantly between treatments, only the biochar derived from seed-processing residues showed a significantly lower yield than the others, which was an unexpected result. The field had been selected for its low P content, and we expected low P availability to limit crop growth and yields in OP and 1P treatments. However, P concentrations in the grain showed the same trend, i.e. no significant differences in harvested P between the treatments. The application of the compost and biochars was done manually, and this method was more challenging to execute properly compared to the granules (TSF) and pellets (MBM) application, which were placed neatly just under the seed. In addition to this, the late sowing and late fertilizer application may also have influenced the results. However, it is clear that the soil provided sufficient P for the crop (same yields in OP, 1P and 2P), most likely due to P reserves in the subsoil. Therefore, it was concluded that it was not possible to assess or distinguish the effects of the RNF on P uptake.



**Figure 31.** Oat grain yield (t/ha), nitrogen and phosphorus content in grain (kg/ha) fertilized with TSF (P0, 1P, 2P) and RNFs of different origins: composted separated digestate (compostdig), meat and bone meal pellets (MBMpellet), biochars derived from raw sewage sludge (biocharslraw), digested sewage sludge (biocharsldig) and plant residues (biocharplant). Error bars and bands represent the standard deviation of the mean (n = 4). Treatments with different letters are significantly different (p < 0.05) according to the Tukey test (HSD).

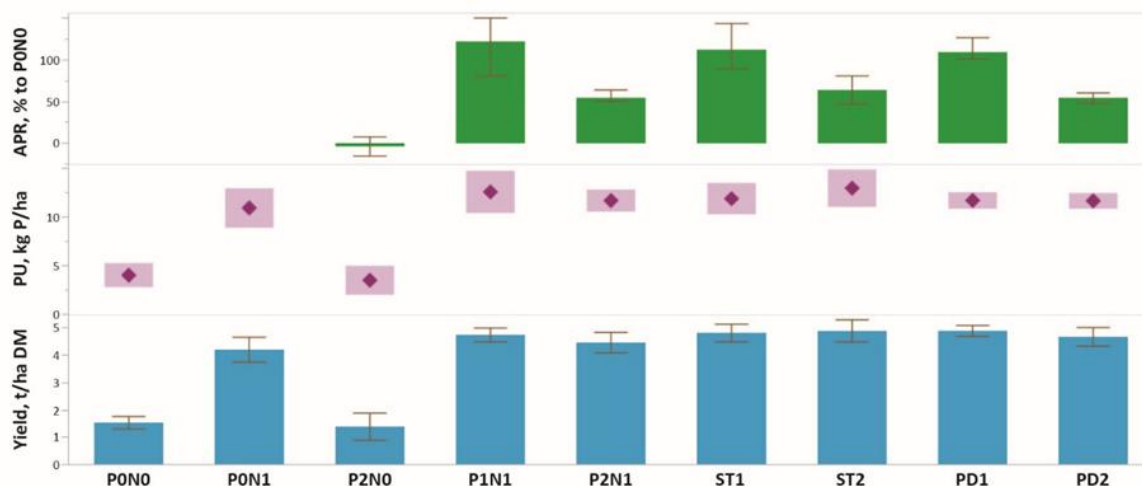
Application of the plant-based biochar resulted in significantly lower N content in grain yields compared to the other treatments. We aimed for an excess of N in all treatments, but most probably there was an overestimation of the amount of plant-available N in RNF. As a result, the observed effect appears to be due to a lower N dose. This may have been caused by the fertilizer’s high C:N ratio, which could have led to N immobilization in the soil.

### Experiment 2025

The grain yield of spring barley, together with phosphorus uptake (PU) and apparent phosphorus recovery (APR), is presented in Figure 32. The lowest grain yields were observed in the unfertilized control (PON0) and in the treatment receiving only P without N (NOP2, 14 kg P/ha as TSP). In contrast, the application of N alone (PON1, 120 kg N/ha) resulted in a substantial yield increase, indicating that it was the primary limiting nutrient under the experimental conditions.

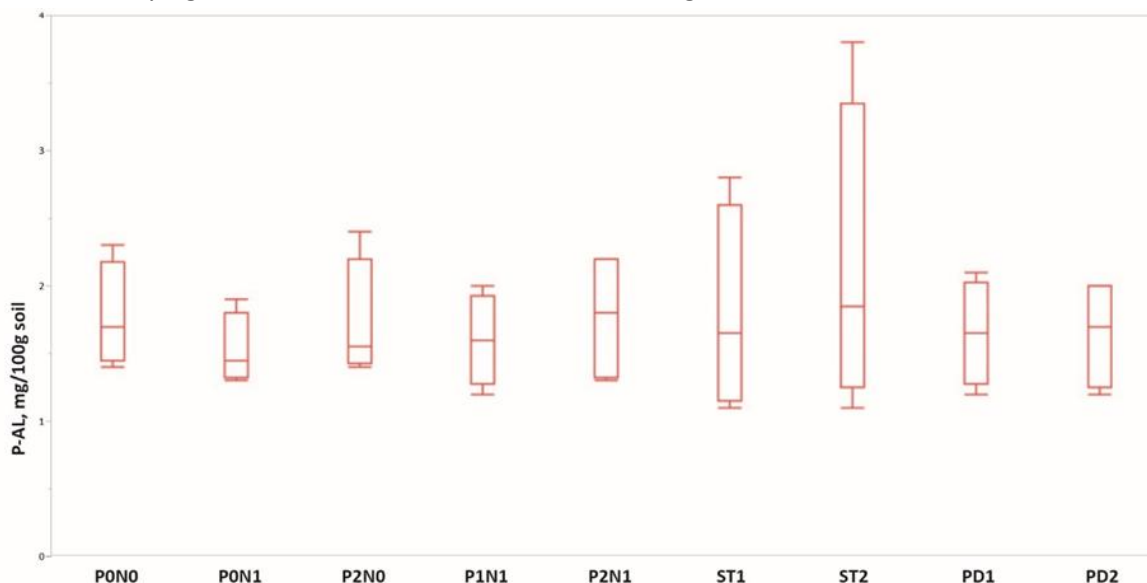
The application of pelletized digestate and struvite produced grain yields in the range of 4.81–4.90 t/ha. However, yields in the TSP and RNF treatments (ST, PD) remained statistically comparable to those of the N-only treatment PON1 (4.21 t/ha). Phosphorus uptake followed the same pattern as grain yield, with higher PU in all N-fertilized treatments and no significant differences among P sources at equivalent P rates.

The APR values with regard to PON0, decreased with increasing P input, reflecting the typical dilution effect where higher P additions reduce recovery percentages even when absolute PU remains similar (Figure 3). Importantly, no statistically significant differences in APR were detected among TSP and RNFs at either P application rate.



**Figure 32. Spring barley grain yield (t/ha), phosphorus uptake by plants (PU, kg/ha), and apparent phosphorus recovery (APR, %).** Error bars and bands represent the standard deviation of the mean (n = 4).

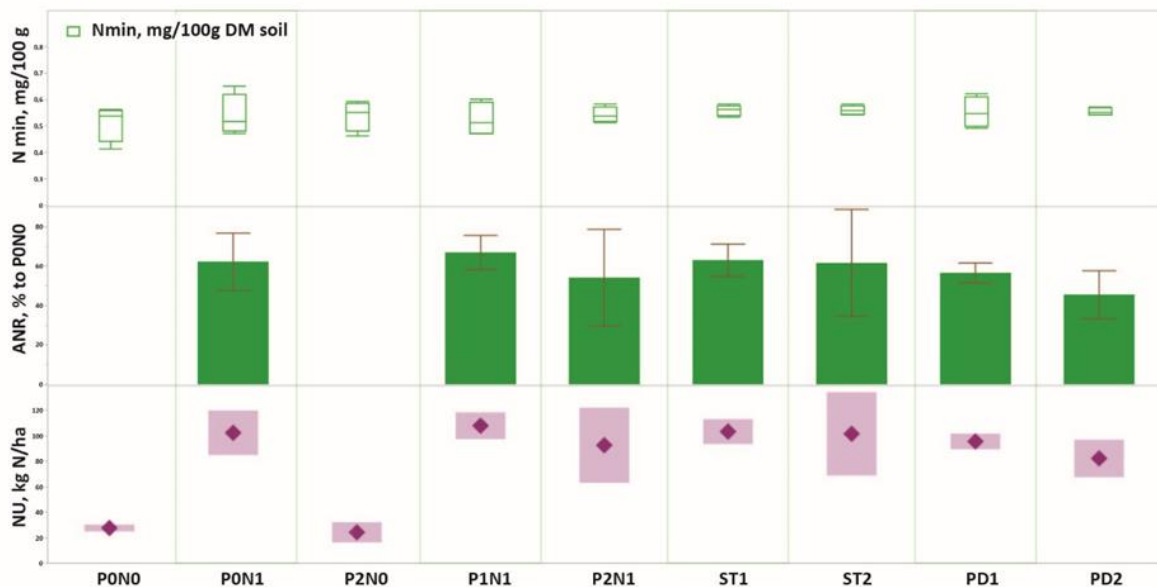
After the harvest, soil P-AL values (Figure 33) remained close to the initial topsoil concentration of 1.6 mg/100 g in the pelletized digestate treatments and in P1N1 and P0N1. Higher P-AL values were observed in the struvite treatments, reaching 2.15 mg/100 g in ST2 and 1.80 mg/100 g in ST1. Both the full-rate TSP treatment (P2N0) and the unfertilized control (P0N0) exhibited similar P-AL values after harvest despite supporting comparable PU and grain yield. This pattern suggests that the applied P in P2N0 did not translate into higher extractable P in the soil, probably because of immobilization. No statistically significant differences were detected among TSP, RNFs, or the control treatments.



**Figure 33. Ammonium lactate–extractable phosphorus (P-AL) in soils after the harvest in 2025.** Error bars and bands represent the standard deviation of the mean (n = 4).

Soil mineral nitrogen concentrations remained within a narrow range across treatments (0.51–0.55 mg N/100 g), indicating that plants in unfertilized plots relied on soil N reserves, while fertilized treatments utilized applied N to support yield formation (Figure 34). In the pelletized digestate treatments, 34% (PD1) and 68% (PD2) of the total N supplied to the crop was intended to come directly from the digestate itself, with the remaining N added as mineral fertilizer to reach the target of 120 kg N/ha. The fact that NU and soil mineral N levels in PD1 and PD2 were comparable to those in the mineral-fertilized treatments indicates that the ammonium-N content and availability in the digestate were sufficient to meet the crop’s N demand. This demonstrates that pelletized digestate

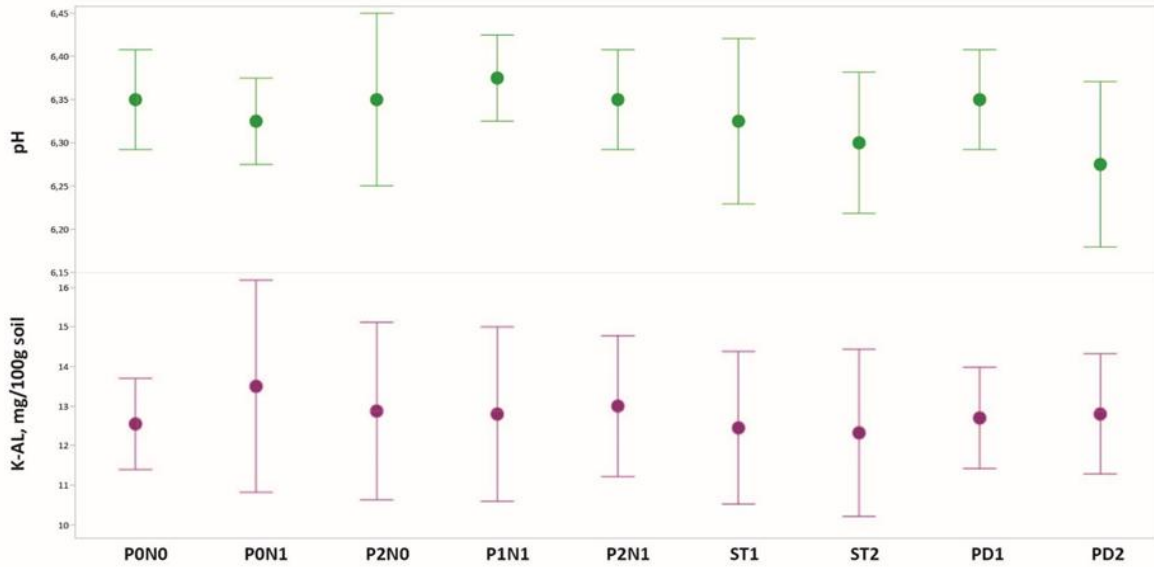
functioned effectively as an N source, contributing substantially to plant N uptake without causing detectable differences in residual soil mineral N.



**Figure 34. Nitrogen uptake by plants (NU, kg/ha), apparent nitrogen recovery (ANR, %), and mineral nitrogen content in soil after the harvest in 2025 (mg/100 g DM soil). Error bars and bands represent the standard deviation of the mean (n = 4).**

Soil pH after harvest showed limited variation among treatments (Figure 35). Neither P source nor P rate produced marked shifts in pH relative to the controls. Extractable K also remained similar across treatments, consistent with the uniform application of potassium in excess. Other soil chemical indicators, including magnesium, sulphur, calcium, iron, and aluminium, also remained unchanged across treatments, and their concentrations in the harvested grain showed no detectable differences.

The absence of clear differences between TSP and the RNF treatments can be partly attributed to the soil P distribution. Although the topsoil was strongly P-deficient (1.6 mg P-AL/100 g), the subsoil contained moderate levels of plant-available P (4–8 mg P-AL/100 g), providing an additional P source once roots extended beyond the upper layer. Under the favourable moisture and temperature conditions of 2025, spring barley likely developed a sufficiently deep and effective root system fast enough to access this subsoil P, thereby reducing the crop’s dependence on freshly applied P in the topsoil. This buffering effect diminishes contrasts in P solubility among fertilizer types. At the same time, the RNFs appeared to release P quickly enough to match the performance of TSP during the growing season, resulting in similar grain yield, PU, and APR across fertilizer sources. The fact that P-AL values remained within the range of 1-3 mg/100 g across most treatments, close to the initial topsoil P-AL of 1.6 mg/100 g, suggests that the soil-crop system maintained a relatively stable extractable phosphorus pool despite phosphorus inputs and crop phosphorus uptake.



**Figure 35. Ammonium lactate–extractable potassium and pH in soil after the harvest in 2025 (mg/100 g). Error bars and bands represent the standard deviation of the mean (n = 4).**

### 3.3.4 Conclusions

Across two consecutive years of field experimentation, the performance of RNFs was consistently comparable to that of conventional mineral fertilizers under conditions of low topsoil P availability. In 2024, grain yields of oats were uniformly high across treatments, and neither mineral P nor RNF applications produced measurable yield differences. This was partly attributable to the low P-AL status of the topsoil and the practical challenges associated with applying non-granulated RNFs such as compost and biochars, which limited the ability to place P close to the seed and thereby evaluate their fertilizer value.

In 2025, with spring barley and pelletized forms of RNF (pelletized digestate and struvite), grain yield, phosphorus uptake, and apparent phosphorus recovery again showed no significant differences between RNFs and TSP at equivalent P rates. Nitrogen availability remained the dominant driver of crop performance, and the RNFs supplied plant-available P and N effectively. The moderate P-AL content of the subsoil likely buffered treatment differences by providing an additional P source once roots extended beyond the P-deficient topsoil.

Together, the results from 2024 and 2025 demonstrate that RNFs can perform comparably to mineral fertilizers under low-P soil conditions in the top-soil layer, provided that N supply is adequate. These findings support the potential of RNFs as viable components of nutrient management strategies, while also highlighting the importance of fertilizer placement and formulation in determining their agronomic effectiveness.

### 3.4. Germany

#### 3.4.1 Methodology

##### Field site

A field experiment with perennial ryegrass (*Lolium perenne* L.) was conducted at the Julius Kühn-Institut, Institute for Crop and Soil Science (JKI-PB), in Braunschweig, Germany (52°17'46.4"N, 10°26'34.9"E). The soil at the experimental site is classified as a Luvisol developed from Pleistocene glacial deposits (Diluvium). The cultivated topsoil is approximately 30 cm deep and has a loamy sand texture, consisting of 69% sand, 24% silt and 7% clay. It is characterized by a low humus content and an arable soil rating (Ackerzahl) of 40.

The experimental crop was sown on 5 September 2024. Soil samples from the plough layer (0–30 cm) were collected on 19 February 2025, prior to the application of the different fertilizer treatments. The topsoil showed high plant-available phosphorus and potassium concentrations with mean values of  $22.9 \pm 1.4$  mg P<sub>2</sub>O<sub>5</sub> and  $22.4 \pm 1.6$  mg K<sub>2</sub>O per 100 g soil, corresponding to VDLUFA supply class D (high). Magnesium concentrations averaged  $5.3 \pm 0.3$  mg per 100 g soil, corresponding to supply class C (optimal). The soil reaction was near neutral (pH  $6.83 \pm 0.10$ ). Mineral nitrogen in the topsoil amounted to  $6.9 \pm 0.5$  kg N ha<sup>-1</sup> at the beginning of the vegetation period, indicating a relatively low available nitrogen supply. Due to the high phosphorus status of the soil, the experiment focused on the effects of nitrogen-rich recycled nutrient fertilizers (RNFs) on plant growth and nitrogen availability.

##### Experimental design and the N-rich fertilizer treatments

The field experiment was established as a randomized complete block design with four blocks, each containing four fertilizer treatments (Figure 36). The treatments consisted of no nitrogen fertilization (N0), mineral nitrogen fertilization using calcium ammonium nitrate (CAN), and two nitrogen-rich recycled nutrient fertilizers (RNFs): sheep wool pellets (SW) and hair meal pellets (HM).

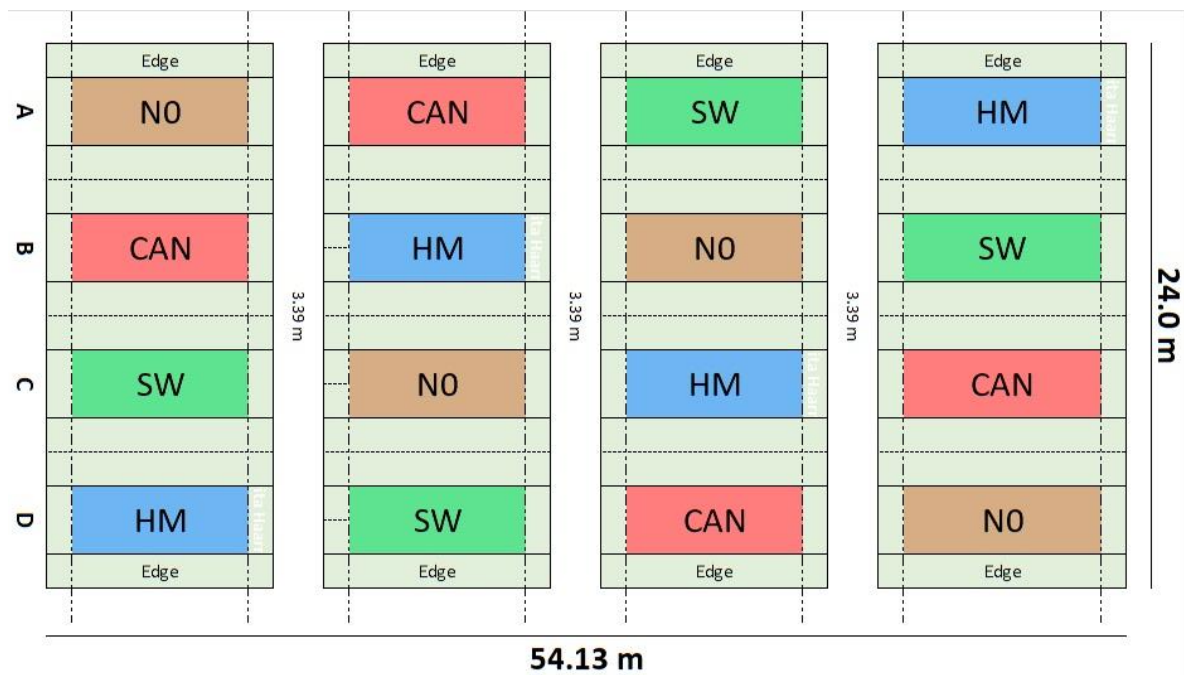


Figure 36. Field trial layout showing the randomized block design with four fertilizer treatments: no nitrogen fertilizer (N0), calcium ammonium nitrate (CAN), sheep wool pellets (SW), and hair meal pellets (HM).

Calcium ammonium nitrate (CAN, 27% N) served as the conventional mineral reference fertilizer. The recycled nutrient fertilizers consisted of pelletized organic materials derived from animal by-products. Hair meal pellets (HM) contain 14 % total nitrogen, mainly present as keratin-bound organic nitrogen originating from processed animal hair. Sheep wool pellets (SW) are produced from compressed and shredded raw sheep wool and contain 10 % nitrogen and 6 % K<sub>2</sub>O. Due to their high keratin content and fibrous structure, these pellets act as slow-release organic fertilizers and can additionally improve soil moisture retention and nutrient availability during decomposition.

### **Management and sampling**

To assess the agronomic use efficiency of the N-rich recycling fertilizers, an experiment management involving a four-time harvest procedure was carried out. Nitrogen was applied in four split applications corresponding to 80, 60, 50 and 40 kg N ha<sup>-1</sup>, resulting in a total nitrogen application of 230 kg N ha<sup>-1</sup> for the fertilized treatments (CAN, HM and SW) in 2025. The amounts of each fertilizer were calculated based on their declared nitrogen content in order to supply equivalent nitrogen rates across treatments. Detailed fertilizer application rates, harvesting dates, and other relevant information are provided in Table 27. A visual assessment of stand development, disease and lodging control was taken before each harvest, while the collection of aboveground biomasses was performed after each harvest, allowing us to evaluate the total dry matter yield and the total nitrogen and phosphorus uptake between the treatments.

**Table 27: Fertilization treatments and harvestings conducted in 2025.**

| Field Management | Date       | Target kg N ha <sup>-1</sup> | Fertilizer treatment            |                                |                                |
|------------------|------------|------------------------------|---------------------------------|--------------------------------|--------------------------------|
|                  |            |                              | CAN (27% N) kg ha <sup>-1</sup> | HM (14% N) kg ha <sup>-1</sup> | SW (10% N) kg ha <sup>-1</sup> |
| Fertilization 1  | 15.03.2025 | 80                           | 296.3                           | 571.4                          | 800.0                          |
| Harvest 1        | 14.05.2025 | 60                           | 222.2                           | 428.6                          | 600.0                          |
| Fertilization 2  | 20.05.2025 |                              |                                 |                                |                                |
| Harvest 2        | 17.06.2025 | 50                           | 185.2                           | 357.1                          | 500.0                          |
| Fertilization 3  |            |                              |                                 |                                |                                |
| Harvest 3        | 06.08.2025 | 40                           | 148.1                           | 285.7                          | 400.0                          |
| Fertilization 4  | 11.08.2025 |                              |                                 |                                |                                |
| Harvest 4        | 20.10.2025 |                              |                                 |                                |                                |

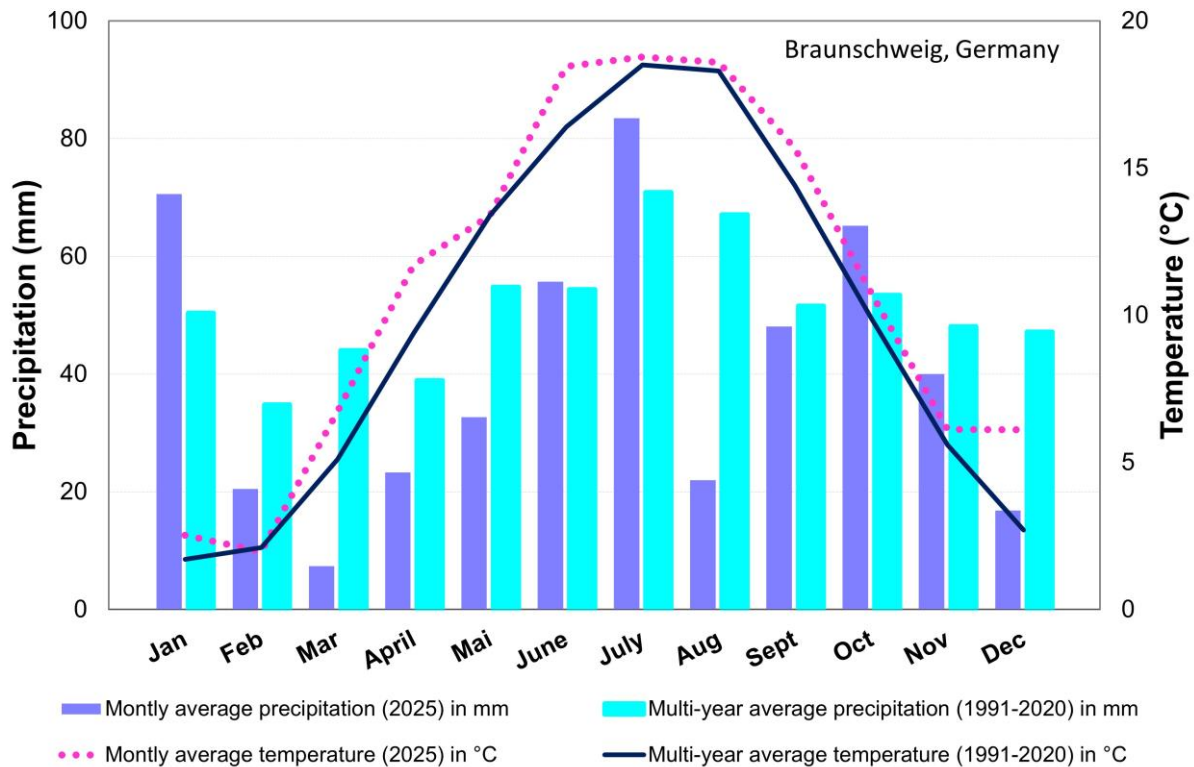
In order to improve fertilization precision between treatments, mechanized application was carried out using the same machinery, see Figure 37. The correct amount of fertilizer was deposited based on the desired quantity and the machine's velocity. This precise technique can reduce the variability of the application rate, improve nutrient use efficiency and reduce environmental impact, offering better control over these factors than manual methods.



**Figure 37. Second field fertilization on 20 May 2025, shortly after the first harvesting. This shows the mechanized application of the fertilizers (right) and the HM RFN pellet fertilizer inside the machine container before application began.**

### 3.4.2. Weather conditions

As shown in Figure 38, the climatic conditions in Braunschweig during 2025 differed noticeably from the long-term average (1991–2020), particularly with respect to precipitation. Mean monthly temperatures during the growing season (March–October) were generally slightly higher than the long-term average, with deviations of up to about 2°C.



**Figure 38. Average monthly precipitation and temperature at JKI-PB institute in Braunschweig during the year 2025, compared to the multi-year average.**

Precipitation showed a more heterogeneous pattern. While January and July received higher rainfall than the long-term average, several months during spring and summer were noticeably drier. In particular, March, April, May and August showed considerably lower precipitation compared with the multi-year mean.

The start of the vegetation period, determined by reaching a temperature sum of 200°C (50% in January, 75% in February, and 100% in March), occurred on 20 March 2025. The first nitrogen fertilization was applied shortly before this date on 18 March 2025.

The first harvest (14 May) followed a relatively dry spring period with below-average precipitation from March to May. The second harvest (17 June) occurred after moderate rainfall in June. The third harvest (6 August) coincided with a pronounced dry phase in summer due to very low precipitation in August. To mitigate drought stress, supplementary irrigation of 30 mm was applied on 5 May, 21 May, 18 June, and 13 August 2025. The fourth harvest (20 October) took place after a wetter early autumn period with precipitation slightly above the long-term average.

### 3.4.3. Results

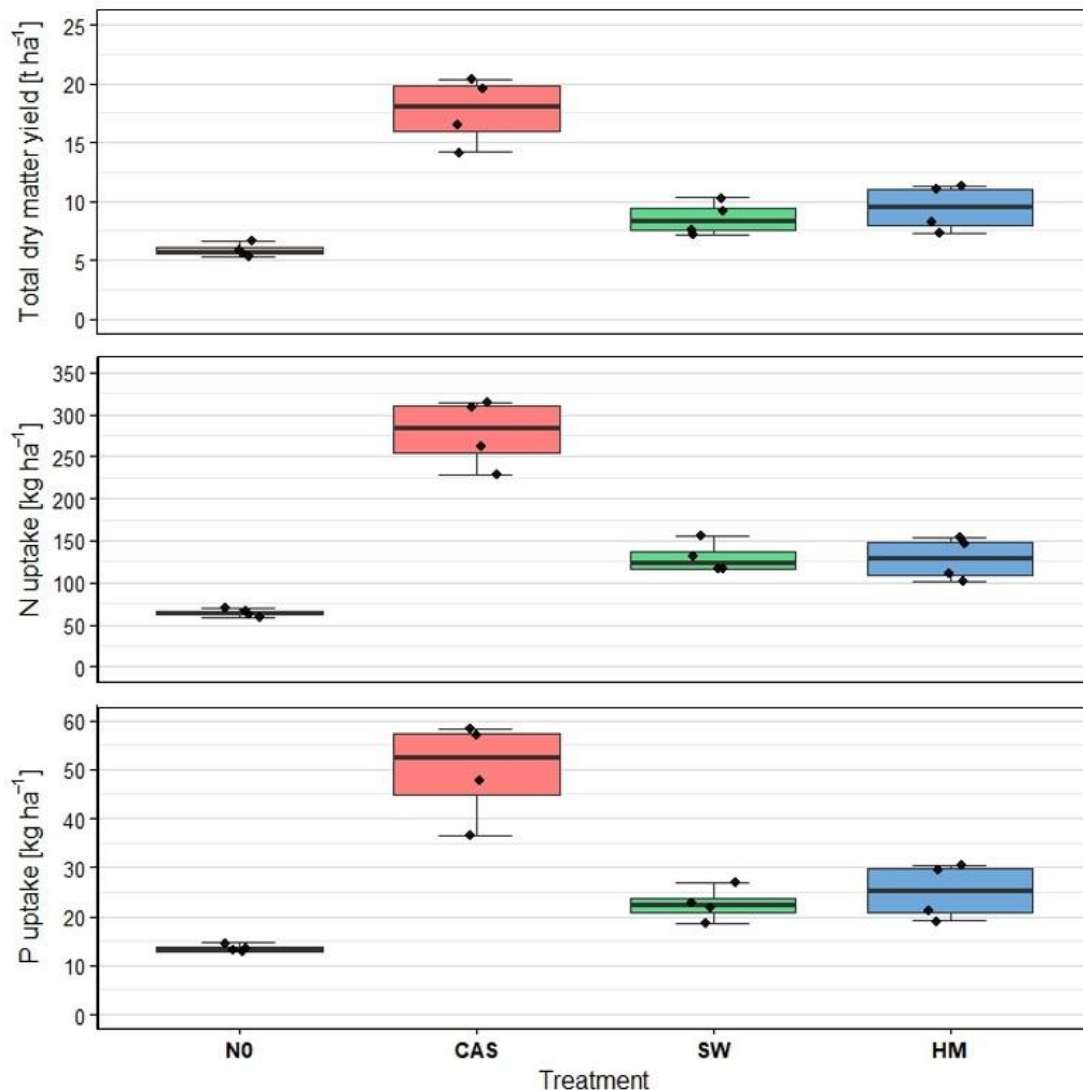
#### Biomass production and nutrient uptake

As shown in Figure 39, the total dry matter yield and nutrient uptake differed clearly among the fertilizer treatments. The unfertilized control (N0) showed the lowest values, with total yields of around 6 t ha<sup>-1</sup> and correspondingly low N and P uptakes. The mineral fertilizer treatment CAN resulted in the highest biomass production, with total dry matter yields reaching approximately 16–20 t ha<sup>-1</sup>. This was accompanied by the highest nutrient removal, with N uptake exceeding 300 kg N ha<sup>-1</sup> in some plots and P uptake reaching up to about 60 kg P ha<sup>-1</sup>.

The two recycled nutrient fertilizers showed intermediate results. Hair meal pellets (HM) produced total yields of roughly 8–11 t ha<sup>-1</sup>, while sheep wool pellets (SW) ranged from about 7–10 t ha<sup>-1</sup>. [interreg-baltic.eu/project/cinurgi](https://interreg-baltic.eu/project/cinurgi)

ha<sup>-1</sup>. Correspondingly, N uptake ranged approximately between 100 and 150 kg N ha<sup>-1</sup> and P uptake between about 20 and 30 kg P ha<sup>-1</sup> for these treatments.

In summary, the greatest biomass production and nutrient uptake were achieved using the conventional mineral fertilizer CAN. However, HM and SW RNFs clearly increased yield and nutrient removal compared to the unfertilized control, although these levels remained below those observed with CAN fertilization.



**Figure 39.** Total dry matter yield, nitrogen (N) uptake, and phosphorus (P) uptake of grassland under four fertilization treatments summed over four harvests (n = 4). Treatments included an unfertilized control (NO), mineral nitrogen fertilization with calcium ammonium nitrate (CAN), and two recycled nutrient fertilizers: hair meal pellets (HM) and sheep wool pellets (SW). Boxplots show the distribution of plot-level values, with individual plots indicated by points.

### Visual assessment of stand development, diseases and lodging

In addition to yield and nutrient uptake measurements, the development of the grass stand was evaluated through visual assessments during the 2025 growing season. The assessments included early biomass development, weed occurrence, stand height, disease symptoms, canopy cover and lodging.

Clear differences between treatments were observed. The mineral fertilizer treatment CAN showed the strongest early growth and the highest stand height during most parts of the growing season. This corresponded well with the higher biomass production recorded for this treatment. In

contrast, the unfertilized control N0 consistently showed the lowest values for early biomass development and stand height. The RNF treatments SW and HM produced intermediate responses. Both treatments improved stand development compared with N0, although values generally remained below those observed for CAN fertilization. SW showed a noticeable increase in stand height later in the growing season and reached values comparable to CAN in autumn.

Weed occurrence was generally low across all treatments. In spring, slightly lower weed cover was observed in the CAN treatment, whereas N0 and SW showed marginally higher values. The HM treatment exhibited the highest weed occurrence in June, although differences between treatments remained small overall. As the season progressed and canopy cover increased, weed presence declined and was negligible from August onwards.

Disease pressure during the season was overall low. Rust and powdery mildew symptoms were largely absent. However, some symptoms of undefined leaf spot diseases were observed in late summer and autumn. Among the fertilized treatments, CAN showed the highest scores, whereas SW exhibited the lowest symptom levels. HM showed intermediate values.

Canopy cover increased strongly in all fertilized treatments and remained highest in the CAN treatment. The RNF treatments SW and HM also produced relatively dense stands, whereas N0 showed the lowest canopy cover throughout the season.

Lodging symptoms were only observed in the CAN treatment during the middle part of the growing season. In contrast, no lodging occurred in the RNF treatments SW and HM or in the unfertilized control N0.

Overall, the visual assessments confirmed the general trends observed in the yield data. CAN fertilization promoted rapid early growth and dense canopy formation, but also showed a higher susceptibility to lodging and leaf spot symptoms. The RNF treatments SW and HM resulted in slightly lower growth but showed good stand stability and comparatively low disease incidence, particularly in the SW treatment.

#### **3.4.4. Conclusions**

The field experiment performed at JKI-PB Braunschweig revealed clear differences among the fertilizer treatments with respect to biomass production, nutrient uptake and stand development. As expected, mineral fertilization with CAN resulted in the highest DM yield, N uptake and P uptake across the growing season in 2025. The rapid availability of mineral N promoted strong early growth, greater stand height and the highest canopy cover. However, this vigorous growth was also associated with a higher susceptibility to lodging and slightly increased leaf spot symptoms compared with the other treatments.

The RNF treatments SW and HM showed intermediate performance. Both treatments clearly increased DM yield and nutrient uptake compared with the unfertilized control (N0), demonstrating that these recycled fertilizers can supply relevant amounts of plant-available N for grassland production. Although total yields remained below those achieved with CAN, the RNF treatments maintained stable stands and good canopy development throughout the season.

The visual assessments further highlighted differences in stand characteristics. While CAN stimulated rapid early biomass formation, the RNF treatments showed a more moderate growth dynamic but maintained high stand stability. Lodging occurred only in CAN, whereas SW, HM and N0 remained free of lodging. In addition, leaf spot scores were lowest in SW, with HM showing intermediate values and CAN the highest symptom levels.

Our experience showed that the mechanized application of the pelletized organic fertilizers was straightforward and that, throughout the entire 2025 growing season, no visual deterioration form of the pellets was observed. Proper management and storage of organic fertilizers is crucial to maintaining their nutrient value, preventing odors and protecting the environment. Now, at the beginning of the 2026 growing season, however, we observed that the SW RNF pellets had changed in their structure, as can be seen in Figure 40. The HM RNF, on the other hand, remains very stable. In this case, we assume that the storage practice of keeping the RNF pellets in their original packaging to prevent degradation was maybe not ideal for this product, which comes in a sustainable paper package. Storing it in a plastic container would probably have been better. The HM RNF came in a plastic bag, which seems to have preserved its stable structure for over a year.



**Figure 40 Pellets form stability of the HM (left) and SW (right) RNFs after one year of storage under proper conditions.**

## 4. Dissemination activities

### 4.1. Estonia

#### Field days in 2024 and 2025

The field days were held on 2. August 2024 and 30. July 2025. The events were participated by farmers, researchers, and plant-production specialists. An overview of the CiNURGi project was presented, highlighting the project's objectives, activities, and expected outcomes. During the field visits, the fertilizers applied in the trials were presented and explained. The broccoli field trials were introduced, and their establishment, management, and current crop status were discussed. Furthermore, in 2025, the winter wheat trial, which was sown after broccoli in 2024, was presented, allowing participants to observe the residual impact of different fertilizers on winter wheat growth and development.



Figure 41. Field visit to Jõgeva field trial station (METK), 2025.

### 4.2. Poland

#### 2024

In 2024, as part of the field experiments conducted in task A 2.3, three promotional meetings were held, which presented the use of RNF fertilizers in agricultural practice. These meetings were attended by participants from various environments related to agriculture, such as students of agricultural universities, agricultural advisors, farmers, scientists, and employees of regional agricultural chemical stations.

#### Synergy workshop CiNURGi & MainstreamBIO projects

On May 28, at the Institute of Cultivation and Soil Science - National Research Institute in Puławy and at the Agricultural Experimental Station in Grabów, synergy workshops of the CiNURGi and MainstreamBIO projects were held (field visit). MainstreamBIO is an EU-funded project (Horizon Europe) that aims to bring small-scale bio-based solutions into mainstream practice in rural Europe by offering innovative digital tools.

The event was divided into two parts:

The first part took place in the Institute's congress hall, where two speakers, Magdalena Borzęcka and Piotr Skowron, presented the results of the MainstreamBIO project, i.e., Toolkit functionalities, and discussed nutrient recycling practices.

The second part was a field trip to the Agricultural Experimental Station of the Institute, where Damian Wach presented the corn cultivation experiment, created as part of the CiNURGi project, aimed at demonstrating the effectiveness of recycled nutritional fertilizers.

The workshops were a good opportunity to promote innovative solutions, such as fertilizers recycled or recovered from organic waste, among agricultural schools and universities, as well as advisory services. During field presentations, recycled fertilizers aroused interest. Questions arose: Is it worth using them? And when they will become widely available in the region.

### **Synergy workshop CiNURGi & NUTRI-CHECK NET projects**

On June 7th, a field visit for the CiNURGi and NUTRI-CHECK NET projects took place at the Agricultural Experimental Station of the Institute of Soil Sciences and Plant Cultivation in Grabów, organized in cooperation with the Agricultural Advisory Center in Radom. The event was attended by invited advisors from local Agricultural Advisory Centers and farmers cooperating with them.

During the meeting, when Dr Piotr Skowron presented the assumptions and objectives of the CiNURGi project, participants asked questions about fertilizer recommendations and the safety of Recycled Nutrient (RNFs) fertilizers, as well as the potential for their use.

Later, the group visited the experimental fields, where Dr Damian Wach presented the methodology and ongoing field experiments with spring wheat and corn. This sparked a discussion on the competitiveness of RNFs compared to mineral fertilizers.

This visit emphasizes the importance of cooperation between agricultural advisory centers, the scientific community, and farmers in raising awareness about the crucial issue of nutrient recovery from various types of biomass.

### **Field visit of employees of the Chemical-Agricultural Station and the Agricultural Advisory Centre**

On August 14th, 2024, at Grabow Experimental Station, a meeting of the IUNG CiNURGi team was organized with representatives (sample takers and chemical analysts) of the Chemical-agricultural Station and advisors from the Central Agricultural Advisory Center.

During the meeting, the assumptions of the CiNURGi project and the problems of recovering nutrients from various types of waste were presented. Participants of the meeting took part in a demonstration of soil sampling using an automatic sampler installed on a quad. During the meeting, participants also went to field experiments conducted in task A2.3 in the CiNURGi project with recycled nutrient fertilizers.



Figure 42. Field visits in Grabów Experimental Station (IUNG), 2024.

2025

### Synergy workshop CiNURGi & FERTITEC projects

On 4 July, a joint CiNURGi–FERTITEC workshop and field visit was held at the Agricultural Experimental Station of the Institute of Soil Science and Plant Cultivation in Grabów, organized by the IUNG team in cooperation with the Agricultural Advisory Center in Radom. Advisors from the Mazovian Agricultural Advisory Center took part in the event.

During the meeting, Dr Piotr Skowron presented the objectives of the CiNURGi and FERTITEC projects. Participants raised questions about fertilizer recommendations, the safety of waste-derived products recognized as alternative fertilizers and RNFs, and their potential use in sustainable farming, including the possibility of replacing part of mineral fertilization.

The group then visited the experimental fields, where Dr Damian Wach outlined the methodology and current progress of winter wheat and maize trials. On-site observations illustrated the effects of partial mineral fertilizer substitution. Discussions focused on the competitiveness of alternative fertilizers compared with mineral products, as well as the current interest in RNFs among farmers working with local advisors.

### Presentation at the Conference of the Polish Agronomic Society

The 11th Scientific Conference of the Polish Agronomic Society, entitled "Contemporary Challenges for Agriculture – Prospects and Directions of Development," took place on September 17-19, 2025. The main organizer of the conference was the Puławy Branch of the Society, and the co-organizer and host was the IUNG-PIB in Puławy. Over 150 people participated in the conference, including specialists from 28 research centers located in various parts of Poland, as well as representatives of agricultural consultancy and practice. The conference focused on the challenges, prospects, and directions of agricultural development. Modern agriculture faces many challenges, which were repeatedly mentioned by the speakers. The most important of these were climate change, soil degradation, limited water resources, food security, biodiversity protection, and growing consumer expectations. Furthermore, the speakers highlighted the prospects for agricultural development, including through biological and technological progress, digitalization, the development of biotechnology, and the implementation of modern agricultural practices. Over 40 scientific reports and almost 80 posters were presented during the conference. One of the lectures was delivered by Dr Piotr Skowron, in which he presented the CiNURGi project – its assumptions and currently available achievements and field experiments testing recycled nutrient fertilizers.



Figure 43. Field visit in Grabów Experimental Station (IUNG), 2025.

### 4.3. Sweden

During 2024, several ongoing activities for supporting the development and use of recycled nutrient fertilizers (RNFs) have been going on in Sweden. For the conditions in Sweden, where agriculture is quite a limited business in total, the most efficient dissemination is through collaboration between activities in different projects. Lanna research station (Skara, SLU) is

coordinating different types of studies and hosts different types of field walks for farmers, advisors, students and other stakeholders.

Specific workshop activities (average number of participants around 20), including RNFs from our field study, were held in March 2024 (organized by SLU Fältforsk), in Dec 2024 (organized by SLU and RISE), in March 2025 (organized by SLU and the Swedish Board of Agriculture), and in Jan 2025 (organized by Biogas solution research center). Strategies for development and use of RNFs in Swedish agriculture are yearly included in courses held at SLU at the bachelor and master level.



**Figure 44.** Field walk in Lanna research station (Skara, SLU), 2025.

#### 4.4. Germany

In 2025, a number of ongoing activities were initiated with the aim of facilitating the development and utilization of recycled nutrient fertilizers in Germany. The Institute for Crop and Soil Science (JKI-PB, Braunschweig) advises and researches (among other activities) in genuine and alternative sources of phosphorus, nitrogen and other essential elements for agricultural practices. JKI-PB coordinates various field trials aiming to evaluate and improve soil and plant health and effectiveness, with a view to the application of sustainable management strategies. Agronomical demonstrations are conducted on a regular basis at JKI-PB with the objective of facilitating the transfer of knowledge between local farms, experts, researchers, stakeholders, students and government authorities.

##### Workshop and group field day

Specifically, a workshop and field day were held at JKI-PB in Braunschweig on 26 May 2025, with around 15 participants, primarily farmers, alongside researchers and plant production specialists. During the event, we introduced the CiNURGi project, outlining its objectives, activities, and expected outcomes. As part of Activity 2.3, we presented our field experiment and shared initial results for *Lolium perenne*. The focus was on the practical performance of N-rich RNFs and our systematic approach to assessing their agronomic effects. A technical description of the investigated RNFs was provided to the participants. The exchange with farmers offered valuable practical insights: one participant reported already using one of the RNFs and expressed satisfaction with its performance,

while also noting that the relatively high costs currently limit its economic viability mainly to organic farming systems or high-value crops such as vegetables.



**Figure 45. Field visit in JKI-PB in Braunschweig, 2025.**

### **Dissemination of the results to the academic community**

As part of the dissemination activities for the CiNURGi project field experiment, we are writing a scientific paper. Also, we are preparing two videos, one demonstrating the practical application of pelletized recycling nutrient fertilizers (RNFs) under field conditions, and another illustrating the quantification of root development using  $\mu$ CT imaging. Additionally, we will present our results at the ESNI-NERM 2026 conference in April in Brussels in the form of a poster. Furthermore, we are contributing to broader CiNURGi dissemination and synthesis activities, including a Baltic Sea Region (BSR) article on circular economy research in the region and the development of policy recommendations within Activity A2.3.

## 5. General summary

Across Estonia, Poland, Sweden, and Germany, the CiNURGi field trials demonstrated that Recycled Nutrient Fertilizers (RNFs) can support crop production under diverse climatic and soil conditions, although their agronomic performance varied depending on product type, fertilizer's nutrient availability, crop species, weather conditions, and initial soil nutrient content. Among all trial countries, Poland and Sweden showed the strongest 'mineral' RNF-to-classic mineral fertilizer equivalence, while Estonia and Germany demonstrated moderate but consistent agronomic benefits, particularly where nitrogen availability supported nutrient uptake. Despite these differences, several cross-country patterns emerged.

In Estonia, RNFs such as struvite-based combinations improved broccoli biomass and nutrient uptake, particularly when paired with readily available nitrogen sources. While mineral fertilizers still delivered the highest yields, RNFs consistently outperformed the unfertilized control and demonstrated clear potential, especially in treatments where nitrogen availability supported phosphorus uptake.

In Poland, RNFs performed comparably to mineral fertilizers in both cereals and maize. Nitrogen rate was the dominant factor determining yield, while nitrogen form had a limited influence. Mineral RNFs such as ASL showed high fertilizer replacement value in wheat and maize (from 95.7% to 105.7%), and organic RNFs (e.g., Planteo pellet) supported maize productivity, stabilizing the yield level, and contributed to improved soil organic matter quality.

In Sweden, RNFs performed similarly to mineral fertilizers under low-phosphorus topsoil conditions. Both pelletized digestate and pelletized struvite supplied plant-available nutrients effectively, and grain yields of oat and barley did not differ between RNFs and conventional P fertilizers. Adequate nitrogen supply remained the key driver of crop performance.

In Germany, RNFs supported grassland biomass production and nutrient uptake at levels intermediate between mineral fertilization and the unfertilized control. While mineral N fertilizer produced the highest yields, RNFs contributed to stable stand development, reduced lodging risk, and maintained good canopy structure. Practical observations also highlighted the importance of proper storage and handling of organic RNF pellets.

Across all countries, soil analyses showed that RNFs did not negatively affect soil pH, macronutrient status, or organic carbon. Organic RNFs often enhanced soil biological activity and had a positive effect on soil organic matter. Residual effects on subsequent crops were generally limited, indicating that most nutrients were taken up during the main growing season.

Together, the multi-country results confirm that RNFs are agronomically effective and can be integrated into fertilization strategies aimed at reducing reliance on mineral fertilizers while supporting circular nutrient flows in the Baltic Sea Region. While these findings are encouraging, they also reflect certain limitations, including crop-specific variability, climatic differences between trial sites, and the constraints of single/dual-season field assessments. Building on this evidence, further steps are recommended to strengthen the knowledge base and accelerate practical uptake. These include conducting multi-season field trials to capture climatic variability, developing region-specific optimisation pathways for RNF technology and application strategies, and supporting farmer adoption through targeted advisory services, demonstration activities, and knowledge-transfer mechanisms. In parallel, policy coherence between EU fertilizer regulation, national nutrient management plans, and regional HELCOM commitments should be enhanced to ensure that

regulatory frameworks, financial incentives, and knowledge-transfer mechanisms work in concert to enable farmers and agri-businesses to operationalize circular nutrient strategies with confidence.

### **Final Outlook**

The 2024–2025 CiNURGi trials confirm that RNFs can effectively substitute a significant part of conventional mineral fertilization without compromising crop performance or soil health. While mineral fertilizers remain superior in terms of safety, rapid nutrient delivery, and end-user trust, ‘mineral’ RNFs effectively compete with them in terms of these properties. Additionally ‘organic’ RNFs offer superior benefits for soil structure, stand stability, and long-term sustainability. Future product and fertilization strategy optimization should focus on synchronizing nutrient release from RNFs with early-stage plant demand and refining the synergistic application of recycled N and P sources to maximize efficiency.