Pilot Biobased Fertilisers Achterhoek

Synthesis Report Monitoring Program Wageningen Environmental Research

Phillip Ehlert

WAGENINGEN
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In het kader van het zesde actieprogramma van Nederland voor de Nitraatrichtlijn werd de gebiedsgerichte Pilot Kunstmestvrije Achthoek uitgevoerd. Wageningen Environmental Research ondersteunde deze pilot met een monitoringsprogramma dat van 2018 tot en met 2021 werd uitgevoerd. Het monitoringsprogramma had als onderwerpen het onderzoeken van risico's verbonden aan het blenden van bio-gebaseerde bemestingsproducten, ondersteuning van demonstratievelden in de praktijk en uitvoering van een viertal wetenschappelijk gebaseerde veldproeven en rapportages van het onderzoek van deze onderwerpen. Dit rapport is het syntheserapport van verkregen onderzoeksresultaten van het monitoringsprogramma.

In the context of the Sixth Action Program of the Netherlands for the Nitrates Directive, the Pilot Biobased Fertilisers Achterhoek was implemented. Wageningen Environmental Research supported this pilot with a Monitoring Program that was carried out from 2018 until 2021. The subjects of the Monitoring Program were to investigate the risks associated with blending of bio-based fertilising products, to support demonstration fields in practice, and to carry out four, scientifically based field trials and reports on the research into these subjects. This report is the synthesis report of research results obtained from the Monitoring Program.

Keywords: biobased fertiliser, nutrient use efficient, nitrogen fertiliser replacement value, grassland, silage maize, sandy soil, mineral nitrogen fertiliser.

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Photo cover: Field experiment on grassland of 2021 near Wageningen

Contents

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Wageningen Environmental Research (WENR) values the quality of our end products greatly. A review of the reports on scientific quality by a reviewer is a standard part of our quality policy. This report was reviewed by dr. G.L Velthof.

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date: 6th April 2022

Preface

In 2018, the regional Pilot Biobased Fertilisers Achterhoek (in Dutch *Kunstmestvrije Achterhoek*) started to find solutions for the manure surpluses in the region. The project was initiated by LTO Noord Projecten and was subsidised by the Province Gelderland. Wageningen Environmental Research of Wageningen University and Research (WENR) was asked to support the Pilot with a Monitoring Program. This request presented a challenge for WENR. WENR was keen to initiate and conduct a Monitoring Program. This program comprised of incubation studies on risk of denitrification and field experiments on grassland and arable land with silage maize and was subsidised by the Dutch Government’s Ministry of Agriculture, Nature and Food Quality. Demonstration fields on grassland of dairy farms were also part of the program and were subsidised by the Ministry (during the program’s first year) and *LTO Noord Fonds, Stichting Biomassa* and *Producentenorganisatie Varkenshouderij* (during the subsequent two years). In the last year of the program, *Melkveefonds* supported additional measurements on the demonstration fields. All parts of the Monitoring Program are reported as individual (annual) reports. This report gives an overview of the results of these studies.

Phillip Ehlert

Summary

The quality of groundwater and surface water in the Netherlands has improved over the past decades, but still requires further improvement (the Netherlands, Sixth Action Program Nitrates Directive 91/676/EEC). The Sixth Action Program of the Netherlands lists a number of measures that contribute to this further improvement. These measures include several pilot projects, one of which is the regional Pilot Biobased Fertilisers Achterhoek (Sixth Action Program of the Netherlands, 5.5.3.3, Annex 1).

Wageningen Environmental Research has supported the regional Pilot Biobased Fertilisers Achterhoek with a Monitoring Program focused on desired product quality and product composition of fertilising products based on animal manure, assessment of their agricultural effectiveness, and the associated environmental risk of nitrate leaching. The Monitoring Program consisted of five parts:

1. Assessment of risks associated with blending of fertilising products based on animal manure, sewage sludge, and mixtures of these.
2. Field experiments conducted in 2019, 2020 and 2021.
3. Demonstration field trials conducted in 2018, 2019 and 2020.
4. Annual technical reports on risk assessment, field experiments and demonstration trials.
5. Synthesis report of parts 1 – 4.

The Monitoring Program started in 2018 and ended in 2021. Technical – scientific reports with results of this program of this period are brought together in this synthesis report for an overall presentation and evaluation.

From a mineral concentrate from co-digested pig slurry, biobased fertilisers (BBFs) were produced by modifying the ratios between nitrogen, potassium and sulphur to crop requirements by adding other nutrients. The added nutrients came from other, preferably secondary, renewable resources, as well as the use of synthetic nitrogen fertilisers. The BBF's used in the experiments, therefore, contained different mineral nitrogen content according to the form of nitrogen (such as ammonium, nitrate and/or urea), and different sulphur content (such as sulphate or organic sulphur). The BBF's were formulated by combining a mixture of condensated ammonia water, urea or urea and ammonium nitrate (called '*Urean' in Dutch*) and/or ammonium sulphate, a biobased product. They were tested in incubation experiments, demonstration fields and field experiments, and met the RENURE criteria.

The mineral concentrate had to meet the requirements which are given in the implementation regulation of the Fertiliser Act (articles 35 a-g of in Dutch *Uitvoeringsregeling Meststoffenwet*). The mineral concentrates always met the RENURE criteria. In addition, 75% of the nitrogen was from bio-based origin.

Blending of mineral concentrate with ammonium nitrate or ammonium sulphate can introduce risks of denitrification of nitrate, or reduction of sulphate to toxic hydrogen sulphide. Denitrification was found to have occurred and formed a risk. No conclusion could be given on the risk of formation of hydrogen sulphide. The methodology requires modification.

Overall, the BBF's tested in demonstration fields and field experiments showed an agronomic effectivity similar to the reference fertiliser, calcium ammonium nitrate. The BBF's produced with condensated ammonia water, however, caused ammonium toxicity and delivered poorer performance

After the harvest of the last cut of grass, or silage maize, the amounts of mineral nitrogen in the soil layer of depth 0-90 cm did not differ between BBFs and the reference fertiliser, calcium ammonium nitrate, at equal application rates of nitrogen.

Based on the experiences from this Monitoring Program, the following recommendations are given.

- Consider using BBFs that meet the RENURE-criteria as a full substitute to synthetic fertilisers.
- Standardise the ration of the digester of GMMC with a focus on standardization of the composition of the resulting digestate of co-digested manure and resultant mineral concentrate.
- Support the production of BBFs with a guided sampling program on composition of digestate and mineral concentrate.
- Initiate additional research on risks on emissions caused by ammonia volatilisation, denitrification (N_2O/N_2) or H_2S.
- Test new innovative BBFs with demonstration fields and field experiments.

Executive summary

The quality of groundwater and surface water in the Netherlands has improved over the past decades, but still requires further improvement (the Netherlands, Sixth Action Program Nitrates Directive 91/676/EEC). The Sixth Action Program of the Netherlands lists a number of measures that contribute to this further improvement. These measures include several pilot projects, one of which is the regional Pilot Biobased Fertilisers Achterhoek (Sixth Action Program of the Netherlands, 5.5.3.3, Annex 1).

Wageningen Environmental Research has supported the regional Pilot Biobased Fertilisers Achterhoek with a Monitoring Program focused on desired product quality and product composition of fertilising products, and assessment of their agricultural effectiveness, and the associated environmental risk of nitrate leaching. The Monitoring Program consisted of five parts:

1. Assessment of risks associated with blending of fertilising products based on animal manure, sewage sludge, and mixtures of these.
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4. Annual technical reports on risk assessment, field experiments and demonstration trials.
5. Synthesis report of parts 1 – 4.

The Monitoring Program started in 2018 and ended in 2021. During this period, the aims of the Pilot were tuned to innovations at Green Mineral Mining Centre (GMMC - or '*Groene Mineralen Centrale' in Dutch*). Originally, the aim was to produce Biobased Fertilisers based on animal manure (BBFs) that could meet criteria of the new European regulation on fertilising products (EC/2019/1009). The focus changed to the production of a mineral concentrate with a low sulphur content to meet crop requirements. Quality parameters of the biobased fertiliser products were adjusted to the by Joint Research Centre (JRC) proposed criteria for REcovered Nitrogen from manURE (RENURE) materials, within the framework of the Nitrates Directive (91/676/EEC). RENURE materials are considered as a replacement for mineral nitrogen fertilisers. The production of a mineral concentrate with a low sulphur content that met the criteria for RENURE materials was realized in 2019, and subsequent years.

From the mineral concentrate, a tailored made biobased fertilising product (BBF) can be made by adding other mineral nitrogen sources to meet different crop requirements (for grass, silage or maize) for nitrogen, potassium and sulphur. Tailoring was based on modifying the ratios between nitrogen, potassium and sulphur to crops requirement by adding other nutrients. The added nutrients come from other, preferably secondary renewable resources, but synthetic nitrogen fertiliser was also used. In the period of the Monitoring Program, resources were condensated ammonia water and ammonium sulphate recovered by stripping ammonia released during composting sewage sludge. Both are biobased nitrogen sources. Also liquid urea (20%N) and a liquid blend of urea and ammonium nitrate (30%N) were used in low quantities. Crops requirement was established by soil testing for fertiliser recommendations. The BBFs ('*Groene Weide Meststof' in Dutch*) differed in composition within in the season. The first cuts of grassland were fertilised with BBFs that were relatively rich in sulphur, while following cuts received BBF's that contained low sulphur contents. BBF's in the experiment had, therefore, different contents of mineral nitrogen with different forms of nitrogen (such as ammonium, nitrate and/or urea), and sulphur (such as sulphate or organic sulphur) created by adding a mixture of condensated ammonia water, ammonium sulphate, urea or urea and ammonium nitrate (called '*Urean' in Dutch*). These BBFs, however, always met the RENURE criteria.

The Pilot was part of the Sixth Dutch Action Program of the Nitrates Directive. The BBF's must meet the requirements of this Program: the mineral concentrate must meet the requirements stated in the implementation regulation of the Fertiliser Act (Articles 35 a-g of the '*Uitvoeringsregeling Meststoffenwet' in Dutch*). In addition, 75% of the nitrogen was from a biobased origin.

Risk of blending

Blending of mineral concentrate with ammonium nitrate or ammonium sulphate introduces risks on denitrification of nitrate or reduction of sulphate to toxic hydrogen sulphide.

Risks of the formation of nitrous oxide due to the addition of nitrate-containing fertilising products (AN) to mineral concentrate and risks of the formation of hydrogen sulphide due to the addition of sulphate-containing fertilising products to mineral concentrate were explored in two studies. The studies comprised of incubation of mixtures under standardized laboratory conditions.

Emission of nitrous oxide (N_2O) was found after a lag-phase when AN was mixed with mineral concentrate. The degree of emission is not solely determined by the amount of added nitrate. A blend of 92% mineral concentrates and 8% liquid ammonium nitrate (150 g N/L) did not lead to a higher degree of denitrification compared to a 4% proportion. However, the process of denitrification started more slowly with an 8% addition.

In this research, a mineral concentrate produced from pig slurry supplied by the company, Agro America, was used. It is possible that this mineral concentrate has a higher content of easily degradable organic matter than a mineral concentrate produced from co-fermented pig slurry (digestate) as produced by GCCM. In that case, the nitrous oxide emission could possibly be lower. Further testing is required to ascertain if biodegradable organic matter becomes a limiting factor when nitrate nitrogen is blended with mineral concentrate.

Loss of nitrate nitrogen was observed during storage of a batch of one of the BBFs made from mineral concentrate (99%) and a liquid urea ammonium fertiliser (‘*Urean’ in Dutch*, (UAN) (1%)), as the nitrate nitrogen content in the IBC container gradually declined. This is an indication that mineral concentrates of digestate mixed with a nitrate-containing fertilising product eventually volatilize by denitrification to nitrous oxide or dinitrogen.

No emissions of hydrogen sulphide were seen when mixtures of ammonium sulphate solution with mineral concentrate produced from digestate were incubated. The technique for measuring this emission of hydrogen sulphide requires modification, and it is not currently possible to conclude if an emission of toxic hydrogen sulphide gas forms a risk. New research has been designed to further investigate these emissions using a different measurement technique, but is not a part of this report of the Monitoring Program.

Demonstration fields

Demonstration fields of grass provided farmers with:

1. Demonstration of the agricultural effectiveness of biobased fertiliser (GMF) with equal amounts of nitrogen, potassium and sulphur compared to a mineral NPS fertiliser blend.
2. Demonstration of the equivalent responsible environmental effectiveness of the GWM with equal amounts of nitrogen, potassium and sulphur compared to a mineral NKS fertiliser blend.
3. An opportunity for the participants to gain experience with the new biobased fertilising product based on animal manure.

Two types of BBFs were tested consecutively. The first two cuts of grass received a sulphur-enriched BBF, on the basis of the grass’s requirement for sulphur, which was established by soil testing. The following cuts received a BBF that was not enriched with sulphur. The results of agronomic effectivity and the environmental risk assessment are, thus, based of a combination of both types of BBFs. The agronomic effectivity was assessed by estimating yields based on measurement of grass heights at about 15 days after fertilisation, and about 10 days before actual harvest. Effectivity was derived from the relative yield estimates. The risk of nitrate leaching was assessed by measuring mineral nitrogen in soil layer depths of 0-30 cm, 30-60 cm and 60-90 cm, before the first fertilization, and after the last cut of grass.

Demonstration fields were created with a simple design: Two treatments (BBF, blend of mineral synthetic nitrogen fertilisers) and one block without repetitions. Both BBF and blend had similar ratios of nitrogen, sulphur and potassium. Ten demonstration fields were created each year. These sites were repetitions, but differed in their fertilisation plans and grassland use. Next, the sites differed in whether they had sprinkler irrigation: Some farmers had the equipment, others did not. Lastly, the sites differed on a yearly basis; ultimately six sites were monitored for three years. The number of sites with differences and variability in the composition of the BBFs during these three years limits detailed analyses focused on long-term effects of the use of BBF.

A treatment without nitrogen fertilisation was lacking in the testing. Yield was estimated by measuring grass height. Chemical analyses of crop nutrients were not conducted. The experimental design did not include a control treatment without nitrogen fertilisation. Therefore, neither nutrient use efficiency, nor nitrogen fertiliser replacement values can be derived from the results from the demonstration fields.

In 2019, the BBF was produced from mineral concentrate and an added biobased condensated ammonia water, as the sulphur content of the mineral concentrate was relatively high. This BBF appeared to cause symptoms of ammonium toxicity in grass from the first cut, directly after application on several demonstration fields. Subsequent cuts were fertilised with a BBF with low or no addition of condensated ammonia water and no symptoms of ammonium toxicity were observed. In 2020, the composition of the BBF had slightly lower nitrogen content than aimed for due to variation in the composition of the mineral concentrate. This caused a slightly lower application rate of nitrogen than planned (approximately 10% less than originally aimed for).

All the experimental years (2018, 2019 and 2020) were years with periods of severe drought in the Achterhoek region. Not all farmers were able to apply sprinkler irrigation. Drought hampered testing of the fertilising products, as drought became a main factor in crop development, and not fertilisation. Drought lowered the effectivity of fertilisation.

The experiences in 2018, 2018 and 2020 were that the agronomic performance of the biobased fertilising product were not significantly different compared to the effectivity of the blend of mineral fertilisers in terms of both yield and residual soil nitrogen after the last harvest, provided that ammonia toxicity was avoided and the nitrogen application rate was based on measurement of the actual batch.

Field experiments

Two field experiments on grass and two field experiments with silage maize were conducted in the period 2019 – 2021. The field experiments served two objectives to assess:

1. Agronomic effectivity: In determining the nitrogen fertiliser replacement value (NFRV) of nitrogen of biobased fertilisers (BBF) made from co-digested animal manure mixed with a liquid blend of urea and ammonium nitrate (UAN, 'Urean' in Dutch), and
2. Environmental risk: In assessing the risk of leaching of nitrogen from these biobased fertilising products.

The experiments used the available biobased fertilisers. The composition of the BBFs changed during the time period due to innovative changes in the production process of the mineral concentrate at GMMC. At the start of the experiment, the ratio of sulphur to nitrogen of the mineral concentrate was relatively high due to the use of sulphuric acid in the reversed osmosis process. Condensated ammonia water, a biobased nitrogen source without sulphur, obtained by an evaporation/stripping process from digestate, was used in 2019 to produce the by required ratio of nitrogen to sulphur, which was determined by soil testing. In 2019, a condensated ammonia water-enriched fertilising product (BBFa+) and a diluted BBFa+ (DBBFa+) were included in the experiments. In 2019, the biobased fertiliser basic (BBFb) was produced with mineral concentrate and 1.5% condensated ammonia water. In 2020 and 2021, BBFb was produced from mineral concentrate and 1% UAN.

Field experiments in 2019 and 2020 (on grass and maize) were carried out under unfavorable growing conditions due to drought and elevated temperatures. Sprinkler irrigation was required in these years to combat drought. The field experiment on grassland in 2021 had favorable weather conditions for the growth of grass.

As reference fertilisers, calcium ammonium nitrate (CAN) and a liquid blend of urea and ammonium nitrate fertiliser (*'Urean' in Dutch*) were used. Cattle slurry (CS) was also included, as this is the standard for use on grassland and on arable land with silage maize.

Grass responded well on nitrogen fertilisation, but silage maize did not show an obvious, clear response. Variation between the repetitions of a treatment with silage maize in 2020 was large, and differences between treatments were rather small. As a consequence, no significant differences between treatments were seen. These findings are thought to be caused by drought and the impact that sprinkler irrigation had on mineralisation of organic soil nitrogen on arable land.

Overall results of NFRV for grassland can be ranked according to: CAN (100%) ~ BBFb ~ UAN > CS +BBFb > CS, but a ranking for the testing of the fertiliser products with silage maize is not obvious. Actual applied rates of nitrogen were used for calculation of NUEs and NFRVs.

On grassland, more nitrogen was applied than was apparent in the total nitrogen uptake by all cuts of grass and in residual soil nitrogen. Evidently, nitrogen was not available for the crop due to soil processes (immobilisation) and/or was lost by the application methods (through, for example, emissions of ammonia, or N_2O/N_2). After the harvest, the soil stock of mineral nitrogen at a similar application rate did not differ between BBFs or CAN.

On arable land (silage maize) and on grassland, mineralisation of soils organic nitrogen contributed to crop-nutrition. Estimates for the quantity of nitrogen mineralized were of a similar magnitude to fertiliser application rates for silage maize, and were considered as the cause of the poor response of silage maize with nitrogen fertilisation. Overall, the field experiments show that the agronomic effectivity of a BBF made from mineral concentrate and another nitrogen and/or sulphur source was similar to the agronomic effectivity of CAN, when used on grassland.

Information about the environmental risk of leaching of nitrate nitrogen came from measurement of the stock of mineral nitrogen in the soil layer with depth of 0 – 90 cm at the start of the experiments before fertilisation with nitrogen, and after the harvest of the last cut of grass of the harvest of silage maize. The environmental risks of leaching of nitrogen of BBFs of GMMC were no different from those of CAN. For silage maize, the variation between replications of a treatment hindered the formation of a robust conclusion on the effectivity.

Conclusions and recommendations

Agronomic effectivity was assessed with different parameters. The results of the demonstration fields are based on estimates of relative yields that were formulated from measurement of grass height at approximately 15 days after fertilisation and approximately 10 days before actual harvest. Results achieved with sulphur-enriched BBFs used for fertilisation of the first two cuts and BBFb for the next cuts were grouped to enable calculation of a relative agronomic effectivity that was derived from estimated yields.

The results of the field experiment are based on measurements of yield and nitrogen uptake, and are defined by nitrogen use efficiency (NUE) and nitrogen fertiliser replacement values (NFRV) per fertilising product.

Drought and elevated temperatures are not beneficial for grass growth (even with sprinkler irrigation), and cause negative effect on yield and nutrient uptake. Drought combined with sprinkler irrigation had an effect on soil processes, as crops without nitrogen fertilisation could still acquire enough nitrogen.

Provided that the constituent components are taken into account, the BBFs demonstrate a similar agricultural activity to a mineral nitrogen fertiliser. Use of condensated ammonia water lowers agronomic effectivity.

From measurement of the soil mineral nitrogen before fertilisation and after the (last) harvest, no indications were found that BBFs led to a higher stock of mineral nitrogen after the harvest compared to a mineral nitrogen fertiliser. Both appear to have similar environmental risks.

All field experiments included treatments without nitrogen fertilisation. These treatments still demonstrated relatively high nitrogen uptake. Combined with measurements of relatively low stocks of soil mineral nitrogen before and after the last harvest, there were indications that the soil contributed nitrogen to the crop. It is thought that the warm weather conditions combined with sprinkler irrigation accelerated soil processes.

Irrigation is thought to have promoted mineralisation of organic nitrogen in the soil on arable land (silage maize).

On grassland, not all nitrogen of fertilising products were accounted for. A part was not traced in the stock of soil mineral nitrogen after the last cut, when nitrogen uptake was taken into account. The total uptake of nitrogen was lower than applied with the fertilising products. After the final harvest, residual nitrogen produced from fertilising was lower than the differences between application rate and nitrogen uptake. Apparently, nitrogen was immobilised or lost (leaching of emission of ammonia or by denitrification).

Based on the experiences from this Monitoring Program, the following recommendations are given.
- Consider the possibility to use BBF's, that meet the RENURE-criteria, as a full substitute of synthetic fertilisers.
- Standardise the ration of the digester of GMMC with a focus on a standardization of the composition of the resulting digestate of co-digested manure and resulting mineral concentrate.
- Support the production of BBFs with a guided sampling program on composition of digestate and mineral concentrate.
- Initiate additional research on risks on emissions caused by ammonia volatilization, denitrification (N_2O/N_2) or H_2S.
- Test new innovative BBFs with demonstration fields and field experiments.

1 Introduction

The quality of groundwater and surface water in the Netherlands has improved over the past decades[1], but still requires further improvement[2] (The Netherlands, Sixth Action Program of the Nitrates Directive 91/676/EEC[3]). The Sixth Action Program of The Netherlands lists a number of measures that can contribute to further improvement. These measures include several pilot projects, one of which is the regional Pilot Biobased Fertilisers Achterhoek (Sixth Action Program of The Netherlands, 5.5.3.3, Annex 1).

The main goal of the regional Pilot Biobased Fertilisers Achterhoek is to investigate the processing of animal manure into valuable biobased fertilisers at a practical level. Different manure processing technologies were reviewed and promising technologies were implemented in practice. Processing leads to new fertilising products. The project will focus on the quality aspects of these new nitrogen (N)-fertilising products based on animal manure, specifically on nutrient levels (N, potassium; K, and sulphur; S), the agronomic effectivity, the level of contaminants (heavy metals, organic micro-contaminants, pathogens, and other contaminants (New Emerging Contaminants (NEC)). These fertilising products will be monitored on composition, agronomic effectivity, and environmental effects in pilots of the Sixth Action Program. The initial aim was to produce products that meet the requirements of the revised EU fertilising products regulation for free trade EC/2019/1009 (currently focused on liquid inorganic NKS fertilising products: PFC1c). During the project, this aim was revised, and the focus became to meet the criteria that are set by JRC proposed RENURE[4] fertilising products within the context of the Nitrates Directive. The monitoring in this project leverages larger monitoring programs of other projects of individual fractions of the fertilising products, such as the thick fraction, the clean water fraction, and other fractions that have also been monitored for the nutrient and contaminant levels[5]. The monitoring of this project on composition, agronomic effectivity and environmental effects is a joint study by the province of Gelderland[6], LTO Noord[7], ForFarmers[8], 'Vruchtbare Kringloop Achterhoek en Liemers'[9], Stichting Biomassa[10] and Wageningen University and Research. There is regional cooperation with a large number of actors involved in the processing of manure at the practical level.

More specifically, the following objectives have been formulated in the regional Pilot Biobased Fertilisers Achterhoek to find solutions for processing manure surpluses in the region:

- Inform, support, and facilitate local land users in their efforts to find circular solutions for manure- and mineral-related issues within their companies. Here, the knowledge from the various 'manure projects' in the province is explicitly included.
- Identify the desired quality and composition of fertilising products from animal manure and sludge that will be available for creating the market product using the best available techniques for processing manure and sludge.
- Advise manure processors, sludge processors and water boards on the desired product (quality), so that a market-oriented offer is created.

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[1] https://www.eea.europa.eu/themes/water/interactive/by-category/nitrate-directive

[2] Van Grinsven Hans J.M. Aaldrik Tiktak. Carin W. Rougoor. 2016. Review. Evaluation of the Dutch implementation of the nitrates directive. the water framework directive and the national emission ceilings directive. NJAS - Wageningen Journal of Life Sciences. 78: 69-84. https://doi.org/10.1016/j.njas.2016.03.010

[3] EC Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates for agricultural sources.

[4] RENURE stands for "REcovered Nitrogen from manURE". RENURE is proposed by JRC in its study SAFEMANURE. RENURE is defined by JRC as any nitrogen containing substance fully or partially derived from livestock manure through processing that can be used in areas with water pollution by nitrogen following otherwise identical provisions applied to nitrogen containing chemical fertilisers as defined in the Nitrates Directive (91/676/EEC), while ensuring the achievement of the Nitrates Directive's objective and providing adequate agronomic benefits to enhance plant growth.

[5] Monitoring is conducted within the H2020 European project Systemic (https://systemicproject.eu/) and the Dutch project Meerwaarde Mest en Mineralen 2 (https://www.wur.nl/nl/project/Meerwaarde-Mest-en-Mineralen-2.htm).

[6] www.gelderland.nl/en

[7] www.ltonoord.nl

[8] www.forfarmersgroup.eu

[9] https://vruchtbarekringloopachterhoek.nl/

[10] https://stichtingbiomassa.nl/

- Create legal space for integral sustainable solutions for the use of minerals in the vegetable and arable production areas, and in the animal sector with grassland and arable land for fodder crops. As a matter of policy, manure and products from manure and sludge must be positioned as valuable secondary raw materials for a circular agricultural practice.

LTO-Noord is the project leader of the regional Pilot Biobased Fertilisers Achterhoek. The project has a practical focus. Farmers who show interest can participate in the Pilot. The Pilot is restricted to 150 participants and 7,500 hectares (ha).

Wageningen Environmental Research (WENR11) of Wageningen University and Research supports this project with a Monitoring Program. This Monitoring Program is detailed and is, therefore, limited to ten participants and approximately 50 ha.

WENR's Monitoring Program is focused on the safe introduction of nitrogen (N) fertilising products in the Achterhoek region by comparing the nitrogen fertiliser replacement value (NFRV; a measure for N use efficiency) to that of regular mineral (synthetic, chemical) N fertilisers and by studying the risk of nitrate leaching.

WENR advises on desired product quality and product composition of fertilising products, and monitors by an assessment of their agricultural effectiveness, and the associated risk of nitrate leaching. The Monitoring Program consists of five parts:

1. Assessment of risks associated with blending of fertilising products based on animal manure, sewage sludge, and mixtures of these.
2. Field experiments conducted in 2019, 2020 and 2021.
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For the positioning of the N fertilising products based on animal manure within legal frameworks on use of animal manure and mineral fertilisers, it is important to gain insight into the NFRV of biobased fertilising products from processed animal manure and their risk on nitrate leaching.

Risks associated with blending of fertilising products from mixtures with animal manure and other (renewable) nitrogen sources are reported by Oenema and Velthof, 1993, Velthof and Oenema, 1993, Regelink et al., 2021[12] and Sigurnjak et al. (2022, in prep.[13]). Risks have been studied in incubation experiments. The results have been reported (Regelink et al., 2021).

The demonstration field trials, Point 3 of the Monitoring Program, started in 2018. Results of demonstration fields carried out in 2018, 2019 and 2020 have been reported (Ehlert & Van der Lippe, 2020a, 2020b; Ehlert et al., 2021). The monitoring on demonstration field trails has ended.

Field experiments on arable land with silage maize were conducted in 2019 and 2020. A field experiment on grassland was conducted in 2020 and was followed by a second field experiment on grassland in 2021. The results with silage maize and grass have been reported (Ehlert, 2020, 2022a, 2022b, 2022c).

With these eight reports, the Monitoring Program of WENR reached a conclusion. This report merges the results of these reports and forms the so called, 'synthesis report'. The synthesis report follows the Monitoring Program.

The Monitoring Program started in 2018. In that year, the Green Mineral Mining Centre ('*Groene Mineralen Centrale' in Dutch*) was under construction, but was not then operational. From 2019 onwards,the Green

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[11] WENR (Wageningen Environmental Research) is one of the research institutes of Wageningen University & Research.

[12] Regelink, I.C., J.L. van Puffelen, P.A.I. Ehlert, O.F. Schoumans, 2021. Evaluatie van verwerkingsinstallaties voor mest en co-vergiste mest. Wageningen. Wageningen Environmental Research, rapport 3120. https://doi.org/10.18174/554452, https://edepot.wur.nl/554452

[13] Sigurnjak, I., Brienza, C., Egene, C., Regelink, I., G. Reuland, Satvar, M., L. Hongzhen, Massimo, Z. Meers, E., 2022. Document on product characteristics, lab results and field trials (year 4). SYSTEMIC Deliverable D1.13. www.systemicproject.eu/downloads

Mineral Mining Centre (GMMC) was operational and produced biobased fertilising products and amongst others, the mineral concentrate that is required for the production of the biobased fertiliser, which was tested in the Monitoring Program. The biobased fertiliser is tailored to the need of the crop by modifying the ratio between the crop nutrients nitrogen, potassium, and sulphur to crop requirements by adding other nutrients. The added nutrients were preferably from secondary renewable resources. In the period of the Monitoring Program, resources were condensated ammonia water and ammonium sulphate that was recovered by stripping ammonia released during composting sewage sludge. A boundary condition of the pilot was that at least 75% of the nitrogen was derived from co-digested pig manure and other secondary renewable resources. During the Monitoring Program, much smaller quantities of a liquid fertiliser based on urea or a blend of urea and ammonium nitrate ('Urean' in Dutch) was used to tailor the composition of the BBF's to crop requirements. The choice of the fertilising products components followed the composition of the mineral concentrate. Initially in 2019, the sulphur content of the mineral concentrate was high from an agronomic perspective, leading to main use as sulphur fertiliser, with nitrogen and potassium as accompanying nutrients. A high sulphur content suits fertilisation of the first two cuts of grassland, but for subsequent cuts, sulphur is not required. The aim of GMMC was, however, to produce a nitrogen fertilising product from co-digested pig manure with potassium and sulphur as accompanying nutrients for all cuts. Therefore, innovation on the reverse osmosis technique was used to produce mineral concentrates with low sulphur content. At the start, GMMC was required to use nitrogen sources without sulphur to tailor the ratios of nitrogen and sulphur to crop requirements. GMMC reduced sulphuric acid use in the reverse osmosis process, leading to a five times lower sulphur content. The resultant mineral concentrate enabled production of biobased fertilisers with different ratios of nitrogen and sulphur. However, reduction of the use of sulphuric acid does have drawbacks. The concentration factors of the nitrogen- and potassium content compared with the contents of these within the ingoing liquid fraction of co-digested pig slurry are lower. Two types of biobased fertilisers are produced by GMMC. One is for grassland in the Netherlands for use before the first two cuts, which require sulphur fertilisation. A biobased fertiliser with additional sulphur from recovered ammonium sulphate is produced. For subsequent cuts, a biobased fertiliser without sulphur is produced through the addition of low quantities of liquid urea or the blend of liquid urea and ammonium nitrate. GMMC's biobased fertilisers are also used for fertilisation of silage maize. In the Monitoring Program of WENR, a biobased fertiliser without the addition of a sulphur source was tested.

The Pilot Biobased Fertilisers Achterhoek began in 2018. Mineral concentrate from another large-scale installation for processing pig manure (not digested) was used initially. From 2019 onwards, mineral concentrate from GMMC was used. GMMC built a new large scale processing installation for co-digested pig manure in 2019. In the start-up phase, adjustments were necessary to achieve the desired product quality. Products made in the second half of 2019 and subsequent years met desired quality standards. Originally, these standards were based on proposals for a new European Regulation for fertilising products (EC/2019/2019). In particular, the compound liquid inorganic macronutrient fertiliser[14]. Reduction in the sulphuric acid used resulted in lower concentration factors for nitrogen and potassium and hindered the fulfilment to criteria of EC/2019/1009. In the same period, the Joint Research Centre (JRC) proposed criteria for nitrogen fertilising products made from manure: the so called RENURE criteria. The fertilising products of GMMC meet the RENURE criteria (Regelink et al., 2021), and as the customers were in the direct neighbourhood of the production location, the GMMC changed focus to these RENURE criteria. The adaption of the processes of the large scale co-digested manure processing plant GMMC and the change in focus of quality criteria to RENURE criteria is a time-sequential event that the Monitoring Program had to respond to. The following chapters focus on the main events of this adaption process, as far as these affected the Monitoring Program.

In Chapter 2, the results of the incubation studies on risks of blending biobased fertilisers are given. Chapter 3 summarises the results of the demonstration fields on grassland of ten dairy farms. The synthesis of the four field experiments on grassland and with silage maize is given in Chapter 4. The evaluation of all results is given in Chapter 5.

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[14] Compound liquid inorganic macronutrient fertiliser: 1.5% N-total, 1.5% K_2O and 0,75% SO_3.

2 Risks of blending biobased fertilisers

2.1 Backgrounds and aims

The composition of a mineral concentrate depends upon the type of manure from which it is produced (pig slurry, cattle slurry, or co-digested manure (digestate)), and the treatment process. As a rule, the ratio between nitrogen, potassium and sulphur of a mineral concentrate requires adjustment in order to be able to meet the demand of the crop (crop requirements) given the soil fertility status of the agricultural plot. This is elaborated by GMMC in the concept of their biobased fertiliser: the Green Meadow Fertiliser (GMF). The composition of the biobased fertiliser was initially tailored to the nutrient requirement of grass and was subsequently also developed for silage maize.

Grass requires extra sulphur alongside nitrogen for the first two cuts. For the first two cuts, therefore, recovered ammonium sulphate (AS) was added to the mineral concentrate of GMMC. This adjusts, i.e. lowers, the nitrogen to sulphur (N/S ratio) ratio. Subsequent cuts require a higher N/S ratio obtained by adding a liquid fertiliser based on urea and ammonium nitrate. This liquid blend of fertilisers in the Netherlands is called 'Urean (UAN)'. Recovered nitrogen in the biobased fertiliser is targeted to proportions higher than 75%. Adding ammonium sulphate (AS) or UAN leads to mixing of mineral concentrate with sulphate or nitrate. In an anaerobic environment, sulphate or nitrate can be reduced by microbiological processes, resulting in the formation of hydrogen sulphide (H_2S) or nitrous oxide (N_2O) and nitrogen (N_2), respectively. Formation of H_2S poses a risk because it is a highly toxic gas. Conversion of nitrate nitrogen to the potent greenhouse gas nitrous oxide (N_2O) or nitrogen (N_2) and lowers the proportion of mineral nitrogen.

GMMC have used other sources for the production of biobased fertilising products with a targeted ratio between the nutrients, nitrogen, potassium and sulphur. These were urea (only in 2018) and condensated ammonia water (only in 2019). Both sources were needed to increase the nitrogen/sulphur ratio. The urea was replaced by UAN. In 2019, the biobased fertiliser was produced from mineral concentrate and condensated ammonia water. Under dry weather and soil conditions, ammonium toxicity on grassland was observed after fertilisation of the first cut. To avoid the risk of ammonium toxicity, condensated ammonia water was discontinued. This nitrogen source was not required, as with progressive insight, GMMC was able to produce a mineral concentrate with a low sulphur content. Tests on the quantity of ammonia volatilisation due to the use of condensated ammonia water were omitted from the Monitoring Program.

Microbiological processes are responsible for the formation of gases (such as N_2O and H_2S). Risks during mixing can be minimized if the fertilisers are mixed just before spreading (fertilising). The microbiological processes then exert little undesirable effect. Storage of the biobased fertiliser with sulphate or nitrate is a risk, as the microbiological processes can occur, due to the duration of the storage. The risks of formation of H_2S and N_2O in mixtures of mineral concentrate and AS or AN have been investigated in two exploratory laboratory studies[15]. Goals of the sub-studies were to determine:

1. If mixing ammonium nitrate (AN) with the mineral concentrate leads to an increased risk of the formation of nitrous oxide (N_2O) during storage.
2. If mixing ammonium sulphate (AS) with the mineral concentrate leads to an increased risk of hydrogen sulphide (H_2S) formation during storage.

Information on the materials and methods used is given by Regelink et al. (2021).

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[15] These studies were subsidised by the ministry of Agriculture, Nature and Food Safety through Top Consortium for knowledge and innovation (TKI), project Meerwaarde Mest en Mineralen - 2 (Dutch) https://topsectoragrifood.nl/project/meerwaarde-mest-en-mineralen-2-2/

2.2 Results

2.2.1 Risk on denitrification

The risk on denitrification was measured by monitoring the flux of N_2O. The risk on denitrification of nitrate of AN was assessed by mixing mineral concentrate with liquid AN (150 g N/L) in mixtures of 100% mineral concentrate and 0% liquid AN, 96% mineral concentrate and 4% liquid AN, or 92% mineral concentrate and 8% liquid AN. As GMMC had to adjust on the reverse osmosis installation at the start of the incubation study, another mineral concentrate of large-scale manure processing plant was used, namely a mineral concentrate of pig manure (not digested) from Agro America B.V. (America, the Netherlands). Production of N_2O was measured ½, 1, 2, 4, 7, 8, 11, 14, 21, 22, 23 and 28 days after applying AN by means of an acoustic gas monitor (Figure 1).

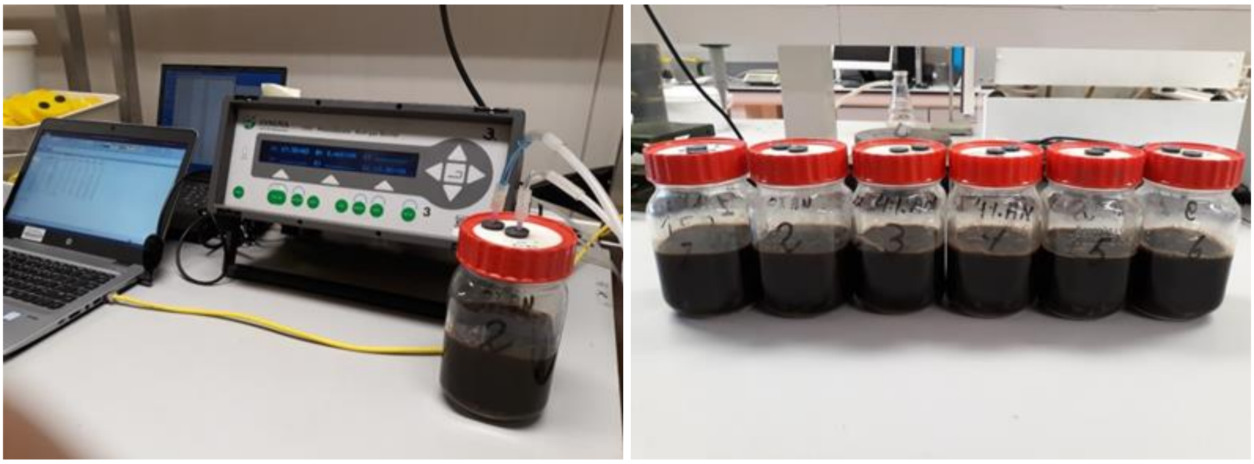

Figure 1 *Left: setup of the acoustic gas monitor with a flux pot. Right: The six flux pots used in the study with the three different treatments. For materials and methods, see Regelink et al. (2021).*

Figure 2 shows the measured nitrous oxide concentration over time. During the incubation period, the lids were kept closed and measurements of the gas composition in the headspace were carried out. The nitrous oxide concentration measured for the control group without added AN was negligibly small over the entire measurement period. A slight increase in the nitrous oxide concentration was measured four days after the addition of AN but was too small an amount to be visible in Figure 2. The concentrations for the treatments of 4% and 8% AN increased significantly only at between 14 and 21 days after the addition (Figure 2). The increase started earlier with the 4% AN treatment than with the 8% AN treatment. In the 4% treatment, the concentration decreased again 35 days after the addition of AN. In the 8% treatment, the concentration decreased again after 42 days. The increase of the nitrous oxide concentration with the 4% AN treatment started earlier than with the 8% AN treatment but stopped earlier.

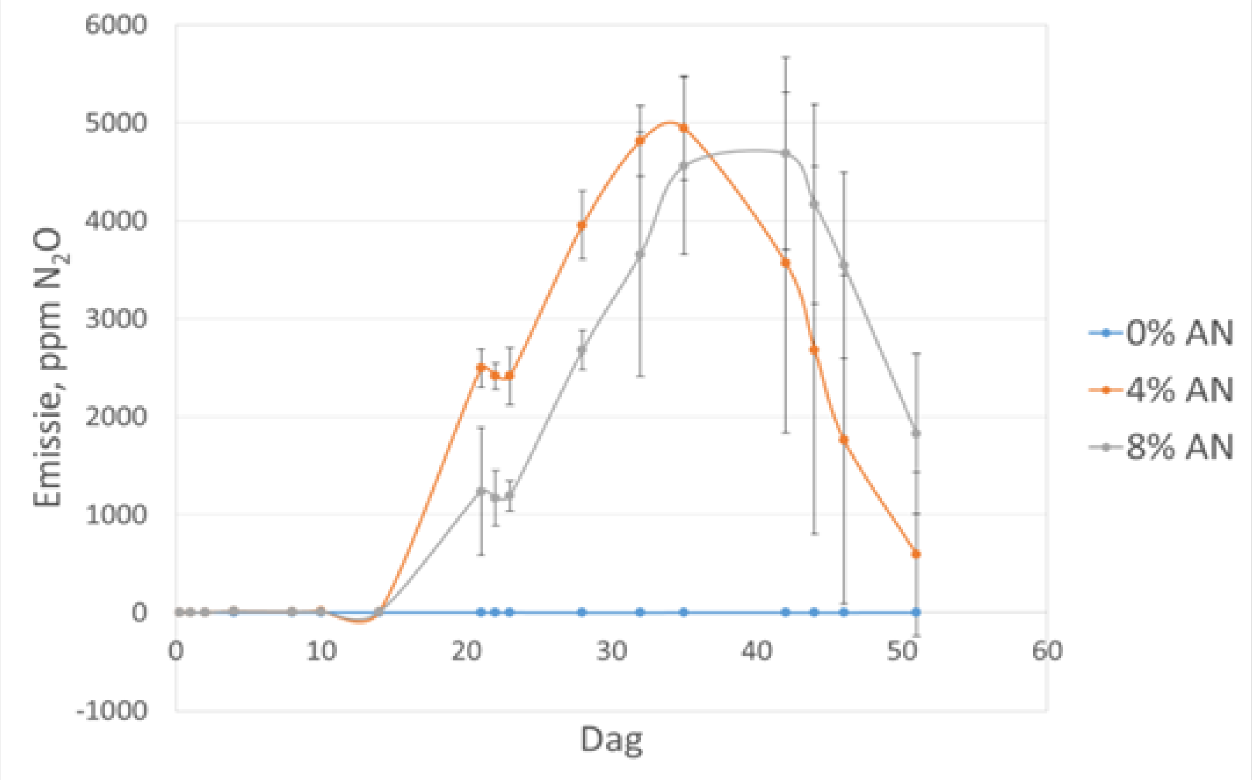

Figure 2 *Nitrous oxide content in ppm N_2O in gas in a sealed flux jar with mineral concentrate mixed with 0%, 4% or 8% ammonium nitrate (AN) for a period of 51 days when incubated at 15°C. The standard deviation based on two repetitions is given with the error bars. High contents are based on an extrapolation of the calibration curve of the acoustic gas monitor and represent an indicative value.*

It was observed that the septa of the flux pots were not convex, from which it was concluded that the headspace had almost ambient pressure (personal comment, Jordy van 't Hull).

The increase in the proportion of AN in an MC from 4% to 8% did not lead to a substantial increase in nitrous oxide contents. There was a delay with the 8% addition compared to the 4% addition. It is not clear what caused this delay. Differences will have been created in EC value and ammonium nitrogen levels and/or contents of decomposable organic matter, but it cannot be concluded from this study if these differences were indeed the causes of the inhibition. From the findings, it can be derived that nitrate addition to the mineral concentrate caused denitrification.

2.2.2 Emission of H_2S

This risk on the formation and emission of H_2S was tested by means of incubation experiments of mixtures of mineral concentrate of GMMC and ammonium sulphate from composting sewage sludge.

The method chosen to measure emission of H_2S was absorption in zinc acetate (ZnAc) according to Eriksen et al. (2012[16]). When H_2S reacts with ZnAc, a precipitate of zinc sulphide (ZnS) is formed. Figure 3 gives the set-up of the incubation experiment.

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[16] Eriksen, J., A.J. Andersen, H.V. Poulsen, A.P.S. Ademsen & S.O. Petersen, 2012. Sulfur turnover and emissions during storage of cattle slurry: effects of acidification and sulfur addition. J. Environ. Qual. 41: 1633 – 1666. Doi: 10.2134/jeq2012.0012

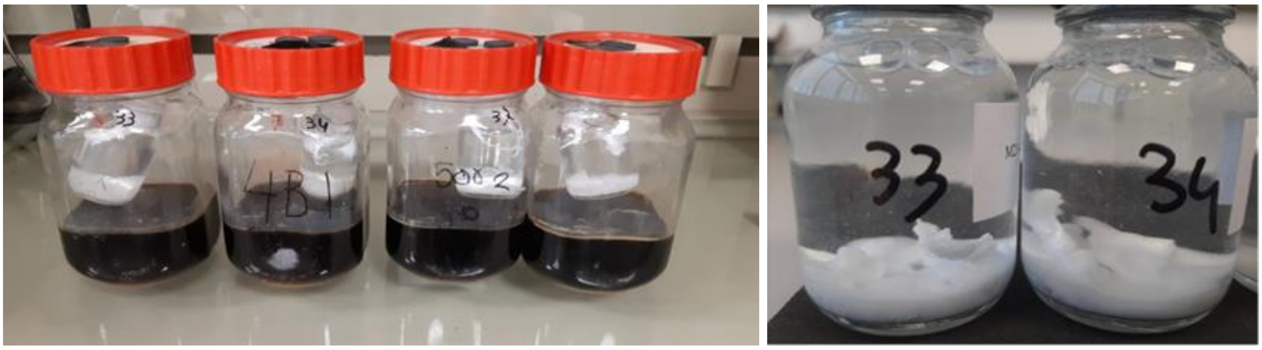

Figure 3 *White precipitate, consisting of fine and larger lumps grown together, in the co-incubated beakers with zinc acetate solution in the flux jars (first incubation experiment). For materials and methods see Regelink et al. (2021).*

In a first incubation experiment, precipitates were immediately formed and grew to large size, which hindered analyses. This experiment used 300 ml mixture with 3% AS and a quantity of 50 ml ZnAc. A second incubation experiment used a larger volume of ZnAc (300 ml) and again a 300 ml mixture. Precipitates were again formed but chemical analyses were not conclusive on the formation of ZnAc. The experiment is inconclusive on the risk on formation of H_2S.

2.3 Evaluation, conclusions and recommendations

Risks of the formation of nitrous oxide due to the addition of nitrate-containing fertilising products (AN) to mineral concentrate and risks of the formation of hydrogen sulphide due to the addition of sulphate-containing fertilising products to mineral concentrate were explored in two studies. The studies comprised of incubation of mixtures under standardized laboratory conditions.

Emission of N_2O was found after a lag-phase after mixing AN with mineral concentrate. The degree of emission was not solely determined by the amount of added nitrate.

In this research, use was made of a mineral concentrate produced from pig slurry by the company, Agro America. It is not known if the content of degradable organic matter of a mineral concentrate differs (i.e. is higher) than of a mineral concentrate of co-digested pig manure. If there are differences, then variation in the potential for denitrification is plausible, but this requires additional testing.

In the context of the Pilot Biobased Fertilisers Achterhoek project, field trials were carried out on grassland and maize land, in which the agricultural effectiveness of the biobased fertiliser based on mineral concentrate (99%) and UAN (1%) was tested. In the context of that study, it was established that the nitrate nitrogen content of a batch of BBF stored in an IBC container[17] gradually decreased over a period of several months during storage in the IBC, and that nitrate nitrogen (NO_3-N) declined from 0.7% to 0%. There is, therefore, an indication that mineral concentrates of a digestate when mixed with a nitrate-containing fertilising product eventually also volatilizes by denitrification to N_2O or N_2.

Emissions of hydrogen sulphide were not observed when mixtures of ammonium sulphate solution with mineral concentrate produced from digestate were incubated. The technique for measuring this emission of hydrogen sulphide requires further modification. New research has been designed to further investigate these emissions using a different measurement technique, but is not a part of this report of the Monitoring Program.

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[17] One batch was made to serve all four fertilised cuts of grass.

3 Demonstration fields at dairy farms

3.1 Backgrounds and aims

The *Achterhoek en Liemers* region has made a case for conducting research at dairy farms. A consortium of interested parties, such as Province of Gelderland, LTO-Noord, Stichting Vruchtbare Kringloop Achterhoek en Liemers, ForFarmers, GMMC and Stichting Biomassa, made advanced plans for conducting agronomic tests at farms. When these tests became part of the Pilot Biobased Fertilisers Achterhoek, a request to WENR was made to include these tests in the Monitoring Program. As part of the Pilot information on the environmental performance was required. These tests are the third topic of WENRs Monitoring Program. Tests were simple demonstration fields, established with the objectives of providing:

1. Demonstration of the agricultural effectiveness of biobased fertiliser (GMF) with equal amounts of nitrogen, potassium and sulphur compared to a mineral NPS fertiliser blend.
2. Demonstration of the equivalent responsible environmental effectiveness of the GWM with equal amounts of nitrogen, potassium and sulphur compared to a mineral NKS fertiliser blend.
3. The opportunity to let participants gain experience with new biobased fertilising products based on animal manure.

Demonstration field trials were established on ten grassland plots of dairy farms. The plots were split into two blocks, one receiving a biobased fertilising product, while the other received a blend of mineral NKS fertilisers. The application rates of N, K and S were based on regular fertiliser recommendations for grassland in the Netherlands derived from soil testing.

Grass yields were estimated by measuring grass height about 15 days after fertilisation and 10 days before the actual harvest.

Environmental effects were monitored through changes in the stock of mineral nitrogen in the soil layers of depths 0-30 cm, 30-60 cm, and 60-90 cm, before fertilisation and after the last cut of grass. Grassland use followed agricultural practices in the Achterhoek, where cattle slurry is used to fertilise three of the five cuts of grass. Therefore, the biobased fertilising product and the blend were additional fertilisers in the nutrient management plan, which was fully based on regular soil testing. The application rates of the nutrients of these fertilisers were exactly the same. The nutrients within the animal manure were taken into account in the nutrient management plan. Results are reported by Ehlert & van der Lippe (2020a, 2020b) and Ehlert et al. (2021)[18].

3.2 Results

Each year, ten demonstration fields were conducted. The fertilisation plan, the composition of the blend and fertilisation recommendations were guided by ForFarmers. GMMC was responsible for the production and composition of the BBF, and the actual fertilisation was carried out with fertiliser equipment that was specially designed for this purpose by Slootsmid. WUR Unifarm and WENR conducted measurements of grass height and residual nitrogen of fertilising products in the soil.

Although there were ten demonstration fields per year, field sites differed due to several reasons. In all years, the experiments took place under dry to very dry weather conditions at elevated temperatures. Approximately half of the participants applied sprinkler irrigation to combat drought, but the other half had to tune their agronomic operations to the moisture available in the soil. One reason for abandoning the Pilot of demonstration fields was poor sod quality. Another reason was a plague of mice. A third reason was a

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[18] In 2018 demonstration fields were subsidised by the Ministry of Agriculture, Nature and Food Safety. In 2019 and 2020 the demonstration fields were subsidised by the Dutch Fund of the Agricultural and Horticultural Organisation North, Biomass Foundation and Farmers Organisation for pig farming. In 2020 Dairy Fund subsidised additional measurements.

shutdown of the dairy farm, which created a split in the grassland plot. And a fourth reason was a conversion of grassland to arable land due to legal provisions. From the 30 demonstration fields, there was one participant who lost interest. In the third year (2020), four plots were identical to the plots of 2018.

Drought caused lowering of yield targets especially for dairy farmers without the means to apply sprinkler irrigation. Drought limited the number of cuts that were harvested. The numbers of harvests, thus, differed amongst participants. Also the time of the harvest or cut varied between the participants. This combined with the limited number of plots which had used of the biobased fertiliser over three years (6 plots), impeded general analyses over three years.

Fertilisation was conducted with biobased fertilisers. The first two cuts received an enriched and sulphur-containing fertilising product. Subsequent cuts received a basic fertilising product only modestly enriched with nitrogen.

In 2018, a mineral concentrate of a large-scale pig manure processing plant was used, as GMMC was not then operational. In 2019 and 2020, GMMC's mineral concentrate was used. In 2019, the mineral concentrate of the production in spring contained high concentrations of sulphur, but by means of a coordinated innovative operation in the processing technique of reversed osmosis in the Summer of 2019, a mineral concentrate with about a five-time lower sulphur concentration was effectively produced. This allowed for the targeted composition of biobased fertiliser for use of fertilisation of grass not requiring sulphur.

Application rates of nutrients followed the general guidelines of the Committee on the Fertilisation of Grassland and Fodder-Crops and were derived from soil testing for fertiliser recommendations of soil samples taken in Spring approximately at a temperature-sum[19] of 200°C.

3.2.1 Composition of biobased fertilisers

The composition of the biobased fertilisers which were used for the demonstration fields were identical to those that were used in practice. The composition changed over the years, 2018, 2019 and 2020 for the reasons given above.

Table 1 *Components of biobased fertilising products (BBF) and their shares in the total composition of the biobased fertilisers used on the demonstration fields of the Pilot Biobased Fertiliser Achterhoek. The enriched BBF's served fertilisation of the first two cuts of grass. The basic BBF's served fertilisation of the subsequent cuts. Enrichment served the increase of the nitrogen content.*

Year	**BBF**	**Components of BBF**	**Share, volume %**
2018	enriched	Mineral concentrate Kumac	93
		Ammonium sulphate (1)	3
		Liquid urea fertiliser	4
	basic	Mineral concentrate Kumac	97
		Liquid urea fertiliser(2)	3
2019	enriched	Mineral concentrate GMMC	94
		Condensated ammonia water (3)	6
	basic	Mineral concentrate GMMC	98.5
		Condensated ammonia water	1.5
2020	enriched	Mineral concentrate GMMC	96
		Ammonium sulphate	2.5
		UAN (4)	1.5
	basic	Mineral concentrate GMMC	99
		UAN	1

(1) Ammonium sulphate from an airwasher/stripper of composting sewage sludge of GMB in Zutphen, the Netherlands.

(2) Liquid urea fertiliser, 20% N (information of GMMC).

(3) Condensated ammonia water), 8% N (information GMMC).

(4) UAN, liquid urea ammonium nitrate fertilisers, 30% N (information of GMMC).

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[19] Sum of all daytime temperatures above 0 degrees Celsius from 1st January.

The composition of the BBF of 2018 and 2019 followed sufficient targeted concentrations and targeted application rates. At the start of the Monitoring Program, targeted concentrations of nitrogen, potassium and sulphur followed the proposal for a new European regulation for fertilising products, namely liquid compound inorganic macronutrient fertiliser. For the production of low sulphur mineral concentration, less sulphuric acid had to be used causing lower concentration of these nutrients in the resultant mineral concentrate. The focus of GMMC changed to criteria proposed by the JRC for the RENURE materials. In the beginning of 2020, the composition of the mineral concentrate had a lower nitrogen concentration than established during the production of the BBFs at the end of 2019, which resulted in a lower application rate of 92% (first two cuts) and 83% (subsequent cuts) than targeted for. For the first cut, the applied rate was a maximum of 6 kg N/ha lower, and for the subsequent cuts, a maximum of 8 kg N/ha lower, but often the deviation of targeted and realised fertilisation with nitrogen was lower (see Annex II of Ehlert et al., 2021).

3.2.2 Agronomic effectivity

Agronomic effectivity was determined in 2018, 2019 and 2020 by measuring grass height at approximately 15 days after fertilisation and approximately 10 days before harvest. In 2018, the harvest dates per cut did not differ much. But in 2019, and even more in 2020, drought and the availability of sprinkler irrigation had a bigger effect on date of harvest, yield, and number of yields. For example, at a given date, on a dairy farm with sprinkler irrigation, a second yield was harvested, while on a dairy farm without the means of sprinkler irrigation, a first cut still had to be harvested. In 2018, grass development between demonstration fields was more in a similar growth stage than in 2019. In 2020, the differences between the demonstration fields in growth stage per cut became larger than in 2019. Measuring grass height as an indicator for yield is reliable to yields of 2.7-ton dry matter/ha. At higher yields, estimation becomes less robust (Holshof & Stienezen, 2016). Due to variation in development of grass per cut between demonstration fields, it could not be avoided to measure grass heights in growth stage larger than 2.7-ton dry matter/ha.

In 2020, additional funding was available[20], which made measurement of actual yield and composition possible, as well as measurement of botanical quality of the grass sod and penetration resistance. It was established that BBF does not lead to a different botanical quality of the grass sod. Due to the different application techniques of a BBF (injection) compared with application of the granular blend, some difference in compaction were found. The blend had compacted soil layers at 30-40 cm depth, while the BBF had compacted soil layers at 70-80 cm depth. The yield of the first two cuts were also measured in 2020. The estimated yield based on measuring grass height were well in line with these measurements (Ehlert et al., 2021). Experiences of 2018 and 2019, and comparison of measured yields and estimated yields[21] demonstrated that grass height measurements for estimating grass yields gives acceptable results for relative comparison of effects of treatments.

This synthesis reports the overall yields per year (Figure 4). For the yields of the individual cuts, the reader can refer to the annual reports (Ehlert & Van der Lippe, 2020a, 2020b and Ehlert et al., 2021). In 2018, a relative effectivity of the BBF of 95% was found. For 2019, this was 89%. And for 2020, this was 88% (Figure 4). In 2019, the mineral concentrate of Kumac was used with a higher addition[22] of mineral nitrogen fertilisers than in 2019 and 2020 (Table 1). In 2019, the first cut suffered from scorching in the first days after application. The scorching was attributed to ammonia toxicity caused by the use of condensated ammonia water. The toxicity caused lower yields. In 2020, the BBFs used on demonstration fields appeared to have lower nitrogen contents caused by different batches mineral concentrate. The actual nitrogen applications rates were lower (Paragraph 3.2.1). It is expected that the agronomic effectivity of the BBF is higher if the full application rate was given: at least above 90%, and possibly 95%.

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[20] Dairy Foundation.

[21] Comparison of measured yields and estimated yields based on measurements of grass height for cut one and two was for measured BBF respectively 94% (9 fields) and 92% (6 fields) and estimated respectively 89% (10 fields) and 93% (7 fields).

[22] In 2018 the composition of the BBF was targeted to proposed criteria of the new European Fertilsing Regulation which led to a minimum of 2% N.

3.2.3 Environmental risk of nitrate leaching

The environmental risk of nitrate leaching was assessed by measuring the stock of mineral nitrogen before fertilisation and after the last cuts in soil layer depths of 0 – 30 cm, 30 – 60 cm, 60 – 90 cm and their totals. The measurements are given for 2018 in Figure 5, for 2019 in Figure 6 and for 2020 in Figure 7. Data are based on results of demonstration field on sandy soils. In 2018, 2019 and 2020, there were one to two demonstration fields on clay soil (different sites) with higher stocks[23] which were not linked with actual fertiliser treatments and clay soil is, therefore, not included.

All demonstration fields used liquid cattle manure ((Ehlert & Van der Lippe, 2020a, 2020b; Ehlert et al., 2021). One dairy farm also applied solid farmyard manure. All dairy farmers were familiar with the application of cattle manure for fertilisation of three cuts. The fertilisation plan consisted of the test products of BBF's and the reference fertiliser - the blend of mineral nitrogen fertilisers with similar ratios of nitrogen, potassium, and sulphur. The residual nitrogen from fertilising products, thus, was derived from cattle manure, BBF or blend.

Differences in botanical composition of the grass sods of the BBF and blend treatment were not found. For both treatments, compaction of sub-soil-layers was seen. For the BBF, compaction was found in the soil layer of depth 70-80 cm, while for the blend compaction was found in the soil layer of depth 30 – 40 cm. This was attributed to the difference in application equipment: adapted sod injector for the BBF and fertiliser spreader of prilled mineral fertilisers with a broadcasting fertilisation-technique (blanket application).

A significant difference in mineral N content in the different soil layers or their totals was found in any of the years. Although in 2019, the BBF tended to have a lower total mineral nitrogen stock in soil. And in 2020, a higher stock. Stocks after harvest of the last cut were significantly higher for all years. Thus, fertilisation led to residues of nitrogen of fertilisers in the soil. Drought is one factor that caused these residues.

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[23] These sites suffered amongst others from plagues of mice.

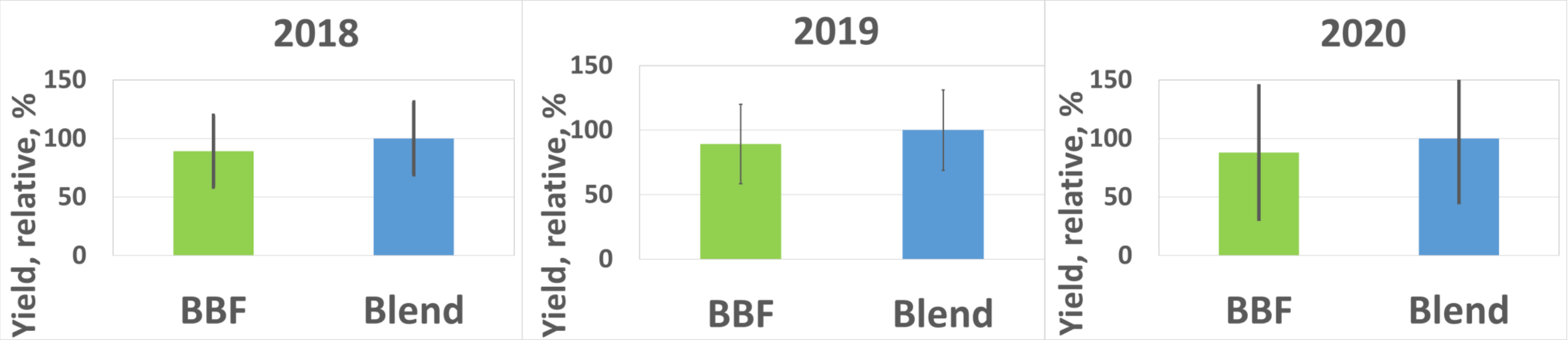

Figure 4 Estimated total yields of grass of biobased fertiliser (BBF) compared to the reference fertiliser - the blend of mineral nitrogen fertilisers. For the first two cuts ammonium sulphate enriched BBF was used; for the fertilisation of the subsequent cuts, BBF basic was used without addition of sulphur and with a lower addition of nitrogen. The target was to formulate blends of mineral nitrogen fertilisers and BBF with identical ratios of nitrogen to sulphur and nitrogen to potassium. This target was accomplished in 2018 and partly in 2019, but in 2019 (partly) and 2020, ratios of respectively nitrogen to potassium and nitrogen to sulphur or potassium were not fully identical. In 2019, the N/K_2O was approximately 1.2 for the BBF, but 2.7 for the blend of fertilising products used for cuts three and beyond. In 2020, for cuts three and beyond, there was a difference in the ratio of nitrogen to sulphur which was 1.5 for the BBF and the blend had a ratio of 3.3.

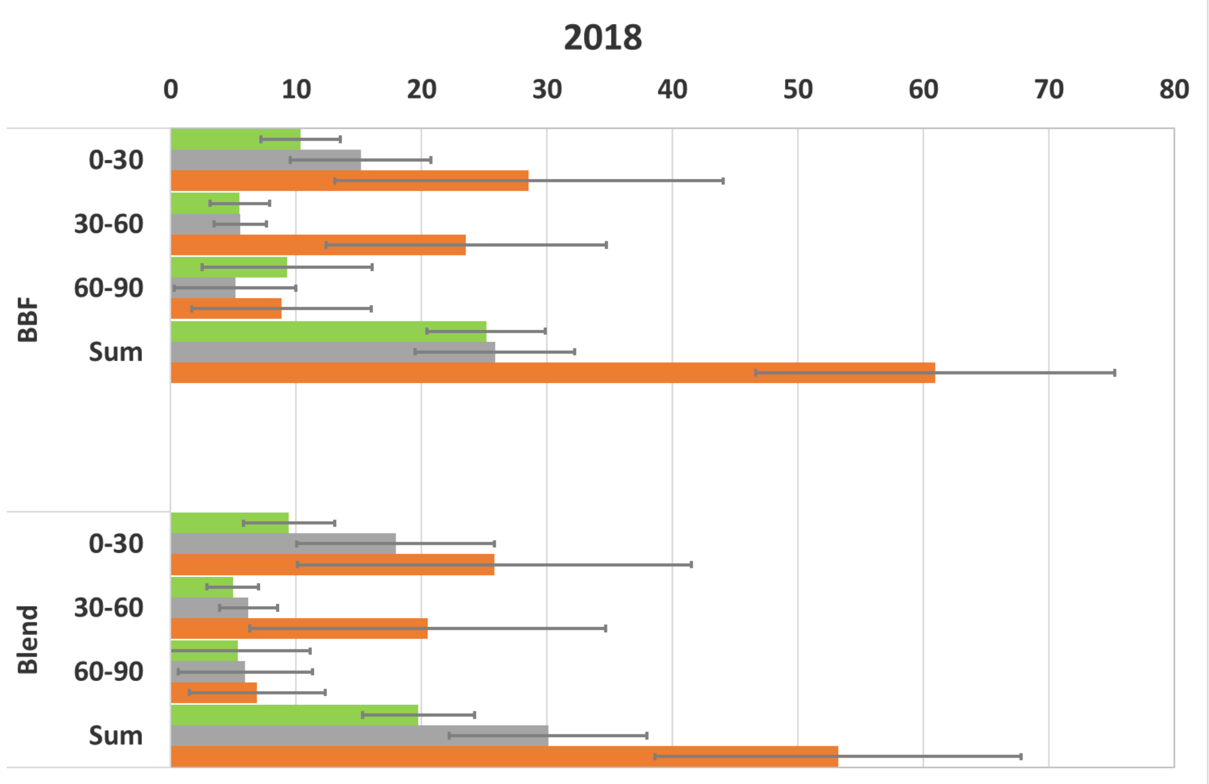

Figure 5	*Stocks of mineral nitrogen in the soil layers of depth 0-30 cm, 30-60 cm and 60-90 cm and the sum over these three layers before the start of the growing season (green bars), after the second cut (grey bars), and after the harvest season (orange bars) for 2018. The vertical lines show the standard deviations of the measured values per treatment and soil layers. Data are based on the sand locations.*

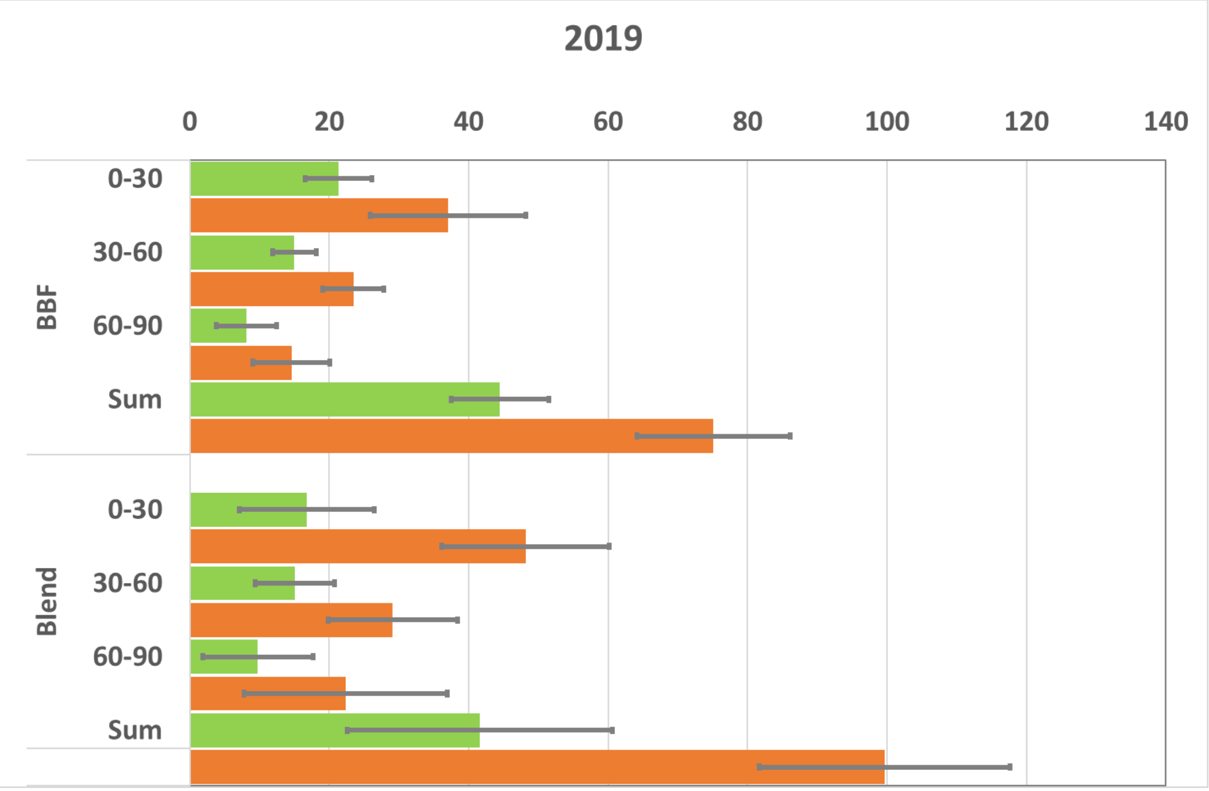

Figure 6	*Stocks of mineral nitrogen in the soil layers of depths 0-30 cm, 30-60 cm and 60-90 cm and the sum over these three layers before the start of the growing season (green bars) and after the harvest season (orange bars) for 2019. The vertical lines show the standard deviations of the measured values per treatment and soil layers. Data are based on the sand locations.*

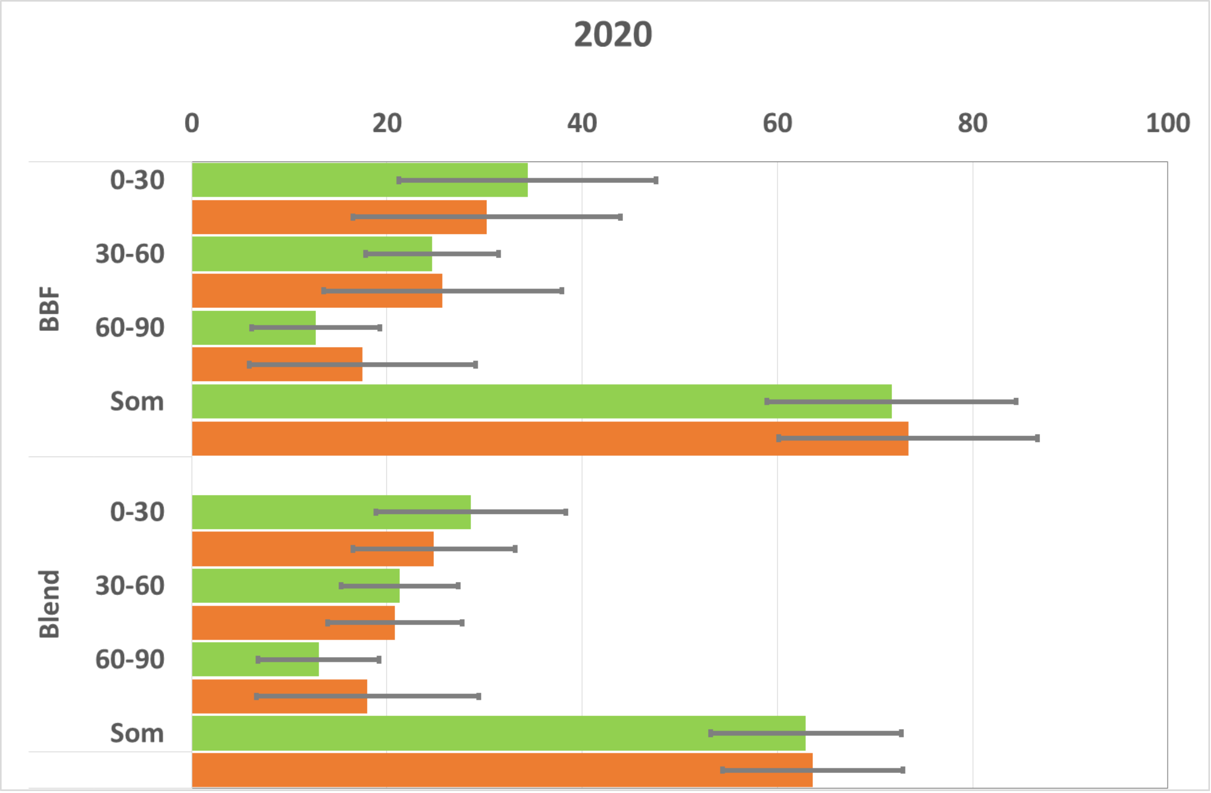

Figure 7 *Stocks of mineral nitrogen in the soil layers of depths 0-30 cm, 30-60 cm and 60-90 cm and the sum over these three layers before the start of the growing season (green bars) and after the harvest season (orange bars) for 2020. The vertical lines show the standard deviations of the measured values per treatment and soil layers. Data are based on the sand locations.*

3.3 Evaluation, conclusion, and recommendations

Demonstration fields were created with a simple design. Two treatments (BBF, blend) and one block without repetitions. Ten demonstration fields were created each year. These sites were repetitions but differed in their fertilisation plans and grassland use. Alongside this, the sites differed in opportunities for sprinkler irrigation. Lastly, sites differed per year. Ultimately, six sites received three years of monitoring. The number of sites with given differences and differences in composition of the BBFs during these three years limited detailed analyses of measurements focused on long-term effects of the use of BBF.

A treatment without nitrogen fertilisation was lacking. Therefore, neither nutrient use efficiency nor nitrogen fertiliser replacement values could be derived from the results of demonstration fields.

All experimental years, 2018, 2019 and 2020, were years with periods of severe drought in the Achterhoek region. Not all farmers were able to apply sprinkler irrigation. Drought hampered the testing of fertilising products, as drought became a main factor in crop development, and not fertilisation. Drought lowered the effectivity of fertilisation.

The experiences in 2018, 2018 and 2020 were that the agronomic performance of the biobased fertilising product approached the effectivity of the blend of mineral synthetic fertilisers with similar ratios for nitrogen, potassium, and sulphur as BBFs in both yield and residual soil nitrogen after the last harvest, provided that ammonia toxicity was avoided and the nitrogen application rate was based on measurement of the actual batch.

Drought affected the growth of grass. Not all farmers had the means to apply sprinkler irrigation causing differences in growth and (estimated) yield of grass. After the harvest of the last cut in general large buffers of mineral nitrogen in the soil layers of depth 0 – 90 cm were found. This indicates an increased risk on nitrate leaching. This can also be attributed to drought.

Differences in botanical composition of the grass sods of the BBF and blend treatment were not found. For both treatments, compaction of sub-soil-layers was found. For the BBF, compaction was found in the soil layer of depth 70-80 cm, while for the blend, compaction was found in the soil layer of depth 30 – 40 cm. This was attributed to the difference in application equipment: adapted sod injector for the BBF and fertiliser spreader of prilled mineral fertilisers.

During monitoring, it was recommended not to use condensated ammonia water. This secondary source of nitrogen is actually not used by GMMC anymore. For guaranteeing of the quality of BBF, organised monitoring of the quality of GMMC is advised.

4 Field experiments with grassland and silage maize

4.1 Backgrounds and aims

Field experiments were conducted to meet objectives that are elaborated in the hypotheses (§ 4.1.1). Measurements were needed to test these hypotheses. Required measurements were yield, nitrogen uptake, nutrient use efficiency (NUE) and nitrogen fertiliser replacement value (NFRV) per specific fertilising product. Field experiments differed in their design from demonstration fields through inclusion of application rates including a control i.e. not fertilised with nitrogen.

The Monitoring Program included four field experiments: two on grassland and two with silage maize. The field experiments with silage maize were conducted in 2019 and 2020 on the sandy soil of the experimental farm, De Marke (Hengelo, Gelderland, the Netherlands).

In 2019, a field experiment on grassland on this farm started, but was stopped prematurely due to excavation works of badgers and an issue of the measured quality of a BBF. This changed the planning. In 2020, a field experiment on grassland on the sandy soil of the experimental farm De Marke was conducted. And in 2021, a field experiment on grassland on the sandy soil of a dairy farm near Wageningen was carried out.

4.1.1 Objectives

The field experiment served two objectives to assess the:

1. Agronomic effectivity. In determining the nitrogen fertiliser replacement value (NFRV) of nitrogen of biobased fertilisers (BBF) made from co-digested animal manure mixed with a liquid blend of urea and ammonium nitrate (UAN, 'Urean' in Dutch) and
2. Environmental risk. Particularly, the risk of leaching of nitrogen from these biobased fertilising products.

The objectives have been elaborated in three hypotheses (§4.1.2). This elaboration was based on the following considerations.

Crop-available N in this study is defined as the quantity of N that is released from a fertilising product during crop growth within a growing season. Commonly, this quantity is assessed by comparison of N uptake by a crop with N from a test-product amended plots with N uptake by the crop amended with mineral N fertiliser, while correcting for the quantity of N taken up from plots without N fertilisation. Nitrogen from a test product that has an equal availability as nitrogen of a synthetic mineral nitrogen fertiliser is expressed by the parameter Nitrogen Fertiliser Replacement Value (NFRV[24]). In the Netherlands, calcium ammonium nitrate (CAN) was used as the reference for assessing NFRV. CAN is a granular (prilled) fertiliser. Prilled fertilisers require a broadcasting fertilisation-technique (blanket application). As biobased N fertilising products are liquids (or suspensions) and often consist mostly of ammonium N, these fertilising products are injected and not broadcasted. Due to the difference in application techniques which can affect NFRV, injection of the liquid fertiliser urea-ammonium nitrate (UAN) was used as a second reference.

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[24] Also called Mineral Fertiliser Equivalent (Jensen, 2013).

Next to the reference fertiliser, the NFRV depends also on the four agronomic fertiliser value determining factors[25]:

- Type of fertilising product,
  - ⇨ The more crop-available N is present, the higher the NFRV becomes.
- Application rate,
  - ⇨ The efficacy of N taken up from a fertilising product decreases with an increase of the application rate.
- Method of application and method of placement of a fertilising product,
  - ⇨ Application methods that do not mitigate ammonia volatilization and denitrification will have a lower NFRV.
- Timing of application of the fertilising product,
  - ⇨ Application well before actual crop growth, increases the risk of nutrient losses to the environment (volatilisation, denitrification, and leaching) and will lower NFRV.

A condition for determining NFRV is that the soil should have low nitrogen availability. A crop has to respond to nitrogen fertilisation in increases of yield and nitrogen uptake to establish NFRV.

The NFRV and residual nitrogen in the soil after the harvest of the last cut of grass were the objects of this study.

4.1.2 Hypotheses

The following hypotheses have been formulated for the biobased fertilising products product by GMMC:

1. The magnitude of NFRV depends on the reference N fertiliser that is used.
2. Biobased fertilising products have a NFRV as the reference fertiliser of nearly 100%.
3. Biobased fertilising products have a similar effect on residual nitrogen after the harvest of the last cut of grass as a regular nitrogen mineral fertiliser (reference) at similar application rates.

In the studies of 2019, 2020 and 2021, several types of biobased fertilising products were tested with different compositions, which followed the fertilising products that were used in farming practice (up to 150 dairy farms and up to 7,000 ha) including the demonstration fields. Progressive insights on steering of process technology of GMMC resulted in different compositions per year. Progressive insights into the application method of the BBFs resulted in the use of especially designed injector equipment. In 2018, a prototype of a BBF injector was used. In 2019, a newly built injector second generation injector was employed. And in 2020 a newly build third generation injector was used. All injectors were built by Slootsmid.

During the Monitoring Program the composition of BBF and its sources changed due to:

- Process technology for the production of mineral concentrate driven by the need to lower the sulphur content to allow for a wider deployment of BBF.
- Agronomic experiences with the renewable nitrogen resource condensated ammonia water.
- Criteria for nitrogen fertilising products based on animal manure with the European context.

Initially the composition of BBF was tailored to use on grassland. For the first two cuts with sulphur-enriched BBF was used, and for the following cuts BBFs without addition of an extra sulphur source. Composition however differed per year (Table 1).

In 2019, GMMC produced a mineral concentrate with relatively high sulphur content but succeeded during that year in lowering this content. This made a wider deployment possible. Secondary raw materials, mineral concentrate and condensated ammonium water served as constituents for these biobased fertilising products. Due to the experience with a mixture of mineral concentrate with condensated ammonium water on grassland on the demonstration field experiments in 2019, when symptoms of ammonium toxicity were observed, the composition of the biobased fertilising product (BBF) was changed in 2020. In 2020, the blend consisted of 99% mineral concentrate and 1% liquid N fertiliser of Urea and ammonium nitrate *('Urean' in Dutch:* 30% N). This fertilising product is called 'Biobased fertilising product basic' (BBFb) in contrast to an

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[25] Also known as the 4R's of nutrient stewardship: right fertiliser type, right application rate, right method of fertiliser application and right period of fertilising.

enriched fertilising product (BBF+), in which ammonium sulphate[26] from an airwasher was used. The mineral concentrates met the criteria for RENURE materials, as proposed by Joint Research Centre (JRC). The composition of 2020 was also used in 2021. Nitrogen in this BBF originated for roughly 75% from digestate and 25% from UAN. This product is referred to as BBF-basic (BBFb). Blending enabled the production of tailormade fertilising products with ratios of nitrogen, potassium and sulphur that fulfil crops-requirement determined by soil-tests for fertiliser recommendations.

4.2 Results

The field experiments of 2019 and 2020 with silage maize and the field experiment of 2020 on grassland were conducted in the Achterhoek region, on the experimental farm, De Marke. The weather conditions for testing of fertilising product were not favourable: drought and elevated temperatures. Sprinkler irrigations were essential. In 2021, a second field experiment on grassland was conducted near Wageningen. The weather conditions of 2021 were favourable for the growth of the grass. All field experiments were on sandy soil.

4.2.1 Composition of the fertilising products

Reference fertilisers were CAN with per kg 275 g total N, 142.5 g NH_4-N and 132.5 g NO_3-N. UAN contained per kg 298 g total N, 71 g NH_4-N, 77 g NO_3-N and 153 g amid-N of urea and had a biuret content of 0.22%. The composition of the BBFs used is given in Table 2 and the ratios between nitrogen and sulphur and nitrogen and potassium in Table 3.

In 2019, an enriched BBF based on condensated ammonia water (BBFa+) was included in the study and also a diluted type with a product/water ratio of 2:1 v/v (DBBFa+). Results with silage maize and results of the demonstration fields indicated ammonia toxicity. In 2020 and 2021, only ammonium sulphate from an air washer from composting sewage sludge and UAF were used to produce BBF+. The BBFb products of 2020 and 2021 all were produced from mineral concentrate of GMMC and UAN.

Tables 2 and 3 with results for all years clearly show the effort of reducing the sulphur content (Table 2) with a higher ratio of N/S as a result. Between the years 2020 and 2021, there is some variation in ratio that is contributed to the digestion process with adaptation of its ration to meet criteria on biogas-production.

In 2019, batches of BBFs were used immediately after production at GMMC. In 2020, one batch of BBFb was produced and stored in IBC until used. Analyses of samples of this BBFb showed a gradual decline of the content of nitrate-nitrogen (Figure 8). For the field experiment of 2020 blending of mineral concentrate and UAF (ratio 99:1) was conducted on the same day as the fertilising product was applied.

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[26] This fertilising products is produced during composting of sewage sludge and is a liquid ammonium sulphate solution with 8% N.

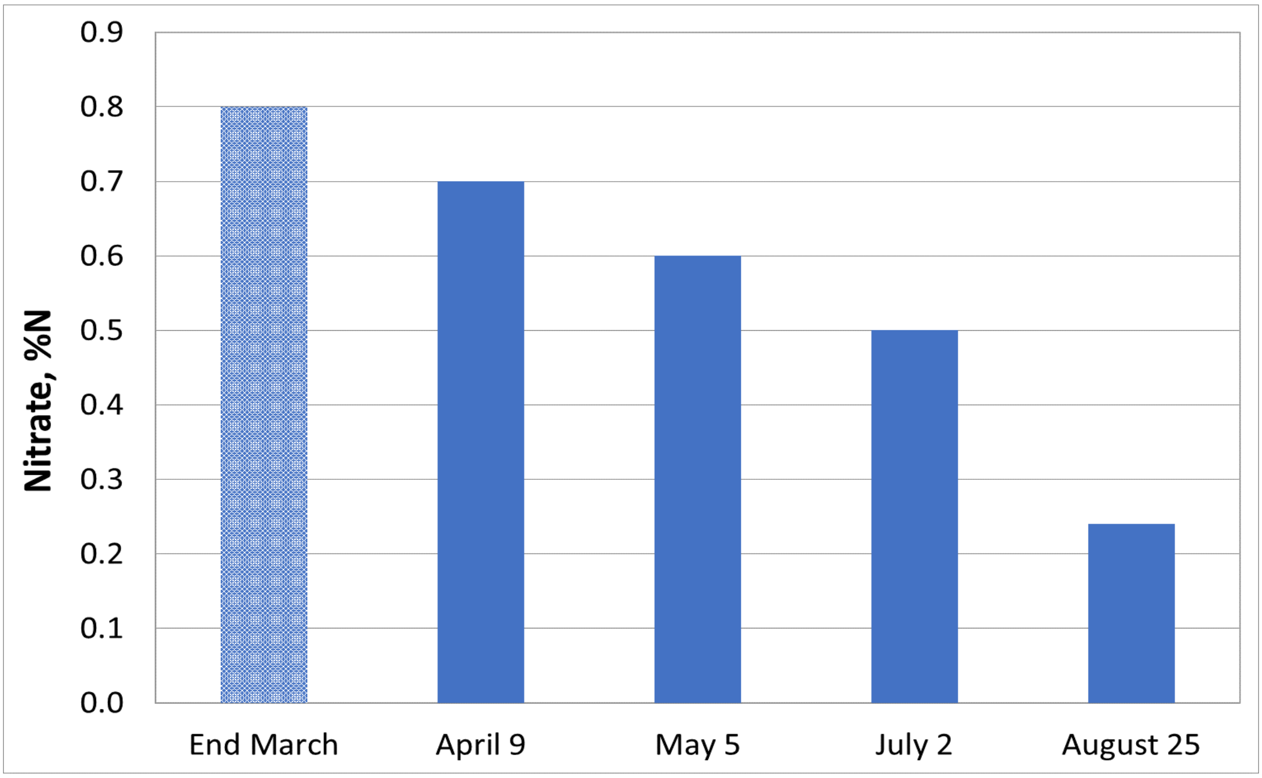


Figure 8 *Content of nitrate nitrogen of one batch of biobased fertiliser basic (BBFb), a blend of mineral concentrate and liquid urea and ammonium nitrate (UAF) in 2020. End March is based on calculation, subsequent months is based on measurements.*

4.2.2 Agronomic efficacy

The weather conditions during the execution of the field trials with silage maize in 2019 and 2020 were dry with elevated temperatures and, thus, the crop required sprinkler irrigation. In addition, the field experiment on grassland in 2020 required sprinkler irrigation, but not in 2021.

In this report, the results of the total yields and nitrogen uptake are given. The results are given in the annual reports (Ehlert, 2020, Ehlert, 2022a, 2022b, 2022c).

4.2.2.1 Grassland

Dry matter yield and nitrogen uptake
In 2020, the fertilisation of the first cut of grass of treatments with UAN received mistakenly both UAN and CAN, thus, receiving a double application rate of nitrogen. In 2021, an enriched BBF (BBF+) instead of a mineral concentrate was used to fertilise grass for the first cut, also creating a higher nitrogen application of 6 – 8 kg N/ha, but this was balanced by a lower nitrogen application rate for the second- and third cuts by applying BBFs produced from mineral concentrate and UAF only.

The grass responded well to nitrogen fertilisation in 2020 and 2021. The response in dry matter yield followed the law of diminishing returns (Figures 9 and 10). Nitrogen uptake increased with increasing application rates (Figures 9 and 10). As at application rates of 100% and 125% dry matter yields levelled off,while nitrogen uptake increased further, this indicates a ‘luxury consumption’ of nitrogen i.e. uptake of nitrogen without a corresponding increase in yield of dry matter.

Overall results of dry matter yields and nitrogen uptake at similar application rates can be ranked according to: CAN ~ BBFb ~ UAN > CS +BBFb > CS.

Table 2 *Composition of the biobased fertiliser tested in the field experiments with silage maize and on grassland in 2019, 2020 and/or 2021.*

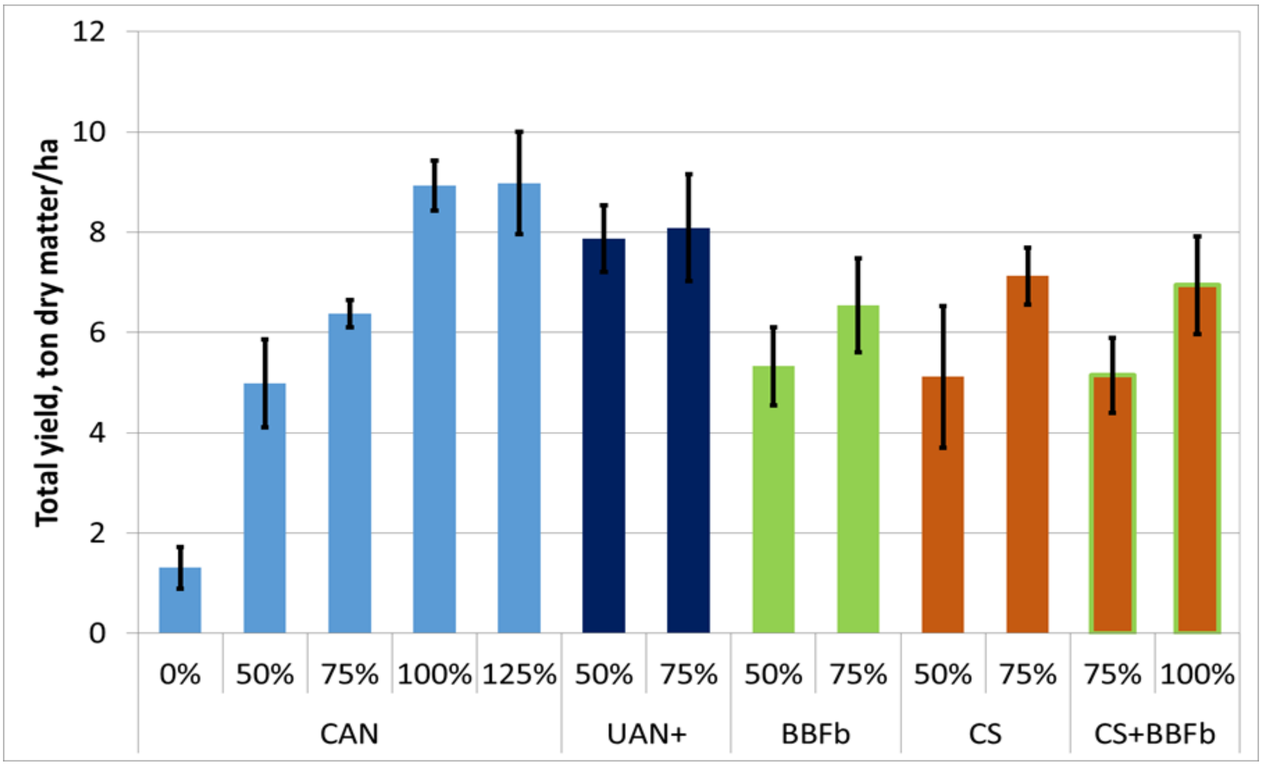
Crop	**Year**	**Fertilising product(1)**	**Cut**	**Dry matter, %**	**Organic matter, %DS**	**EC, mS**	**Bulk-density, kg/L**	**pH**	**N-total, g N/kg**	**NH_4-N, g N/kg**	**NO_3-N, g N/kg**	**P, g P/kg**	**K, g K/kg**	**Mg, g Mg/kg**	**S, g S/kg**	**Na, g Na/kg**
Silage maize	2019	CS	*	7.8	79.2	20.5	990	7.19	4.02	2.2	*	0.43	5.02	0.63	0.54	*
		BBFb	*	4.2	32.4	80.6	1037	8.89	11.49	9.5	*	0.089	6.85	0.053	5.10	*
		BBFa+	*	4.2	31.8	89.1	1051	9.13	15.90	11.9	*	0.060	7.09	0.035	5.34	*
		DBBFa+	*	3.4	32.3	74.1	1035	9.16	12.39	9.8	*	0.066	5.62	0.042	4.07	*
Silage maize	2020	CS	*	8.1	80.4	18.2	1006	6.97	3.87	1.9	*	0.44	4.06	0.66	0.51	*
		BBFb	*	3.8	23.3	74.5	1044	8.35	10.39	8.2	0.7	0.047	8.29	0.057	1.83	*
Grassland	2020	CS	1	8.0	80.0	19.7	998	7.2	3.8	2.2	*	0.40	4.1	0.59	0.50	0.49
			2	7.4	79.7	18.5	1005	6.9	3.4	1.6	*	0.36	4.0	0.54	0.39	0.40
			3	7.2	79.4	18.6	1015	7.0	3.1	1.7	*	0.37	4.3	0.59	0.40	0.39
		BBFb	1	3.8	24.0	73.7	1041	8.2	10.0	8.0	0.7	0.058	8.17	0.072	1.79	4.8
			2	3.6	21.3	77.5	1030	8.7	10.8	8.7	0.6	0.027	8.44	0.039	1.91	4.3
			3	3.6	21.1	77.9	1046	8.7	10.3	9.2	0.5	0.020	8.52	0.044	1.79	4.1
			4	3.5	21.3	74.7	1039	8.8	10.2	9.3	0.24	0.023	7.98	0.035	1.77	4.2
Grassland	2021	CS	1	10.7	68.6	16.6	1000	7	3.7	1	0	0.75	4.16	0.86	0.52	0.67
			2	9.2	53.1	17.0	1001	7.1	3.2	1.9	0	0.68	4.1	0.49	0.54	0.64
			3	6.6	74	18.8	1016	7.5	3.8	2	*	0.49	3.9	0.76	0.37	0.39
		BBF+	1	5.3	38	98.0	1048	8	15.2	11.5	0.7	0.07	9.46	0.07	5.3	3.02
		BBFb	2	3.7	19.6	78.3	1027	8	11.3	9.2	0.1	0.06	9.0	0.0001	1.53	2.85
		BBFb	3	3.8	28.5	78.7	1035	8.2	11.9	8.8	0.8	0.06	8.7	0.0001	1.85	2.84

(1) Fertilising products Cattle Slurry (CS), biobased fertiliser basic (BBFb), biobased fertiliser enriched with condensated ammonia water (BBFa+), biobased fertiliser enriched with condensated ammonia water diluted with water product/water ratio of 2:1 v/v (DBBFa+).

Table 3 *Ratios or nitrogen to potassium (N/K) and nitrogen to sulphur (N/S) of the biobased fertiliser tested in the field experiments with silage maize and on grassland in 2019, 2020 and/or 2021.*

Crop	**Year**	**Fertilising product**	**Cut**	**N/K, [g/kg]/[g/kg]**	**N/S, [g/kg]/[g/kg]**
Silage maize	2019	CS	*	0.8	7.4
		BBFb	*	1.7	2.3
		BBFa+	*	2.2	3.0
		DBBFa+	*	2.2	3.0
Silage maize	2020	CS	*	1.0	7.6
		BBFb	*	1.3	5.7
Grassland	2020	CS	1	0.9	7.6
			2	0.9	8.7
			3	0.7	7.8
		BBFb	1	1.2	5.6
			2	1.3	5.7
			3	1.2	5.8
			4	1.3	5.8
Grassland	2021	CS	1	0.9	7.1
			2	0.8	5.9
			3	1.0	10.3
		BBF+	1	1.6	2.9
		BBFb	2	1.3	7.4
		BBFb	3	1.4	6.4

For converting ratios of N/K to N/K_2O multiply with 1.205, for converting ratios of N/S to N/SO_3 multiply with 2.5.



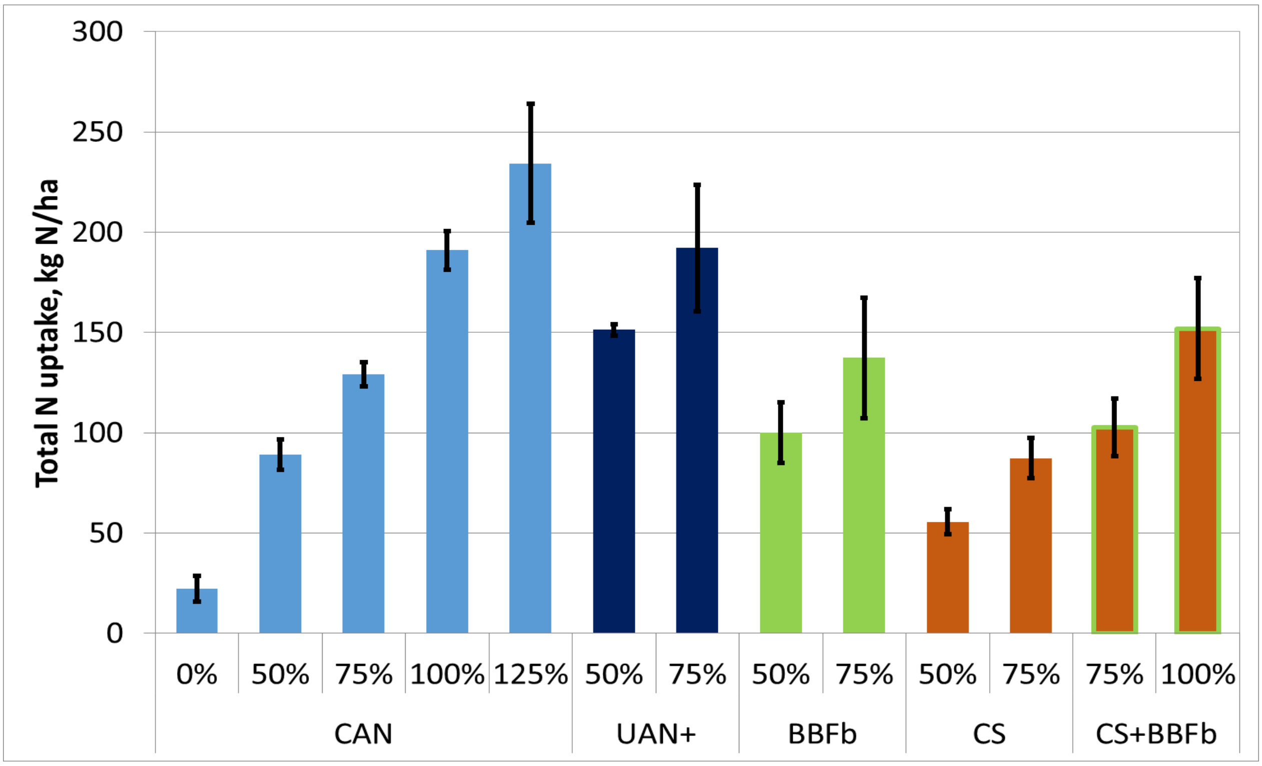
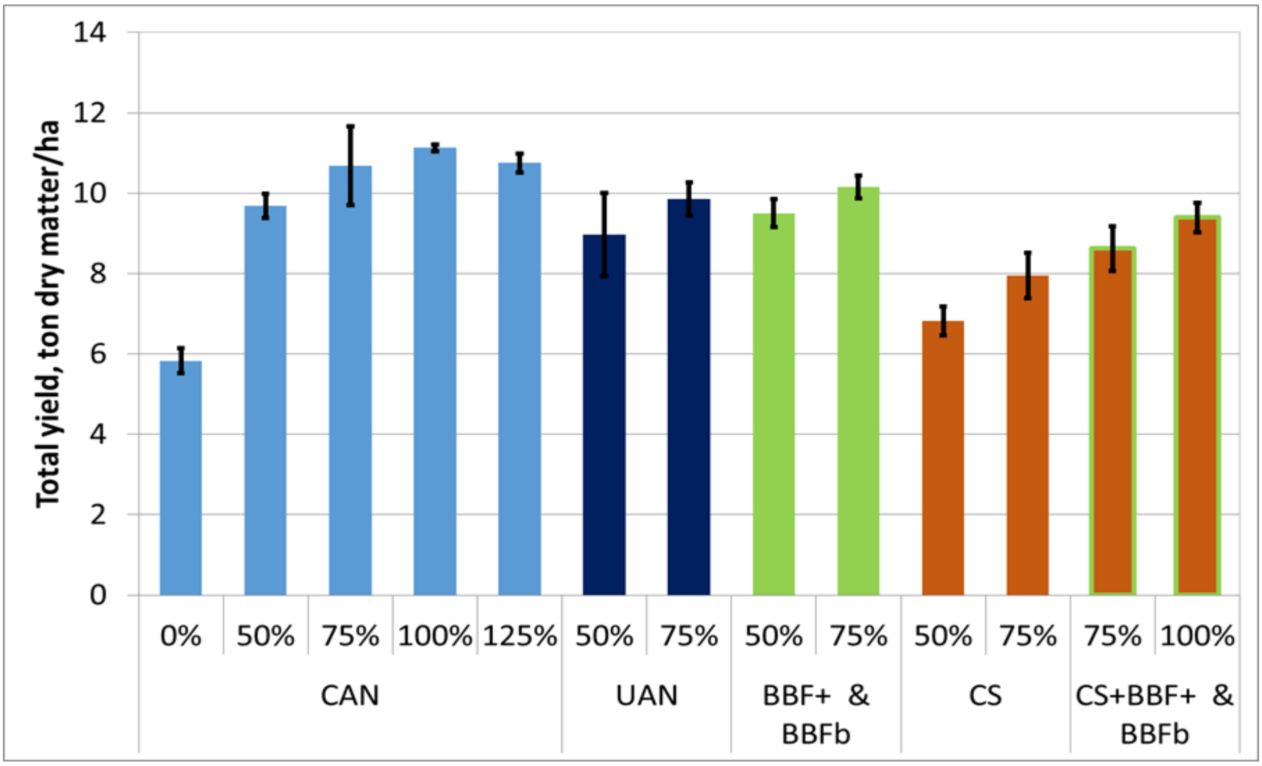


Figure 9 ***Above***: *Total yield of four cuts of grass in ton dry matter/ha for 2020 for CAN, UAN, Biobased fertiliser (BBF), Cattle Slurry (CS) and the combination with CS and BBF at application rates of nitrogen of 0%, 50%, 75%, 100% and 125%. Vertical bars represent standard deviations.* ***Below***: *Nitrogen uptake by four cuts of grass in kg N/ha for 2020 for CAN, UAN, Biobased fertiliser (BBF), Cattle Slurry (CS) and the combination with CS and BBF at application rates of nitrogen of 0%, 50%, 75%, 100% and 125%. Vertical bars represent standard deviations. UAN mistakenly received for the fertilisation of the first cut also CAN, hence the code is UAN+.*



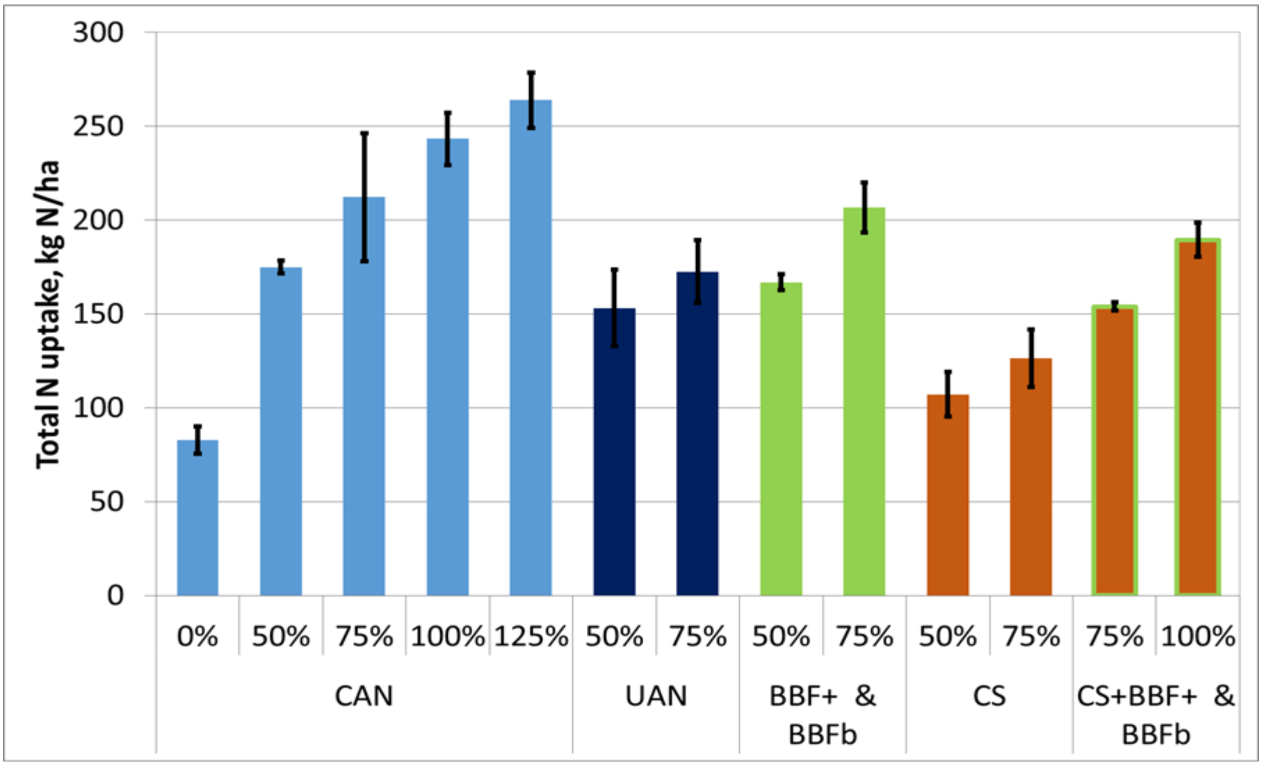


Figure 10 ***Above:*** *Total yield of grass for three cuts of grass in 2021 in tonne dry matter/ha for CAN, UAN, Biobased fertilisers BBF+ (1st cut), BBFb (2nd and 3rd cut), Cattle Slurry (CS) and the combination with CS and BBF+/BBFb at application rates of nitrogen of 0%, 50%, 75%, 100% and 125%. Vertical bars represent standard deviations.* ***Below:*** *Nitrogen uptake by grass in kg N/ha for CAN, UAN, Biobased fertiliser (BBF+ 1st cut, BBFb 2nd and 3rd cut), Cattle Slurry (CS) and the combination with CS and BBF+/BBFb at application rates of nitrogen of 0%, 50%, 75%, 100% and 125%. Vertical bars represent standard deviations. BBFb mistakenly received for the fertilisation of the first cut an BBF enriched with ammonium sulphate and UAF, hence the code is BBF+BBFb.*

NFRV

Values for NFRV are given in Table 4. Due to the mistakenly double fertilisation of grass for the first cut in 2020, the results for NFRV are not given. In 2021, UAN equalled CAN for the first cut but was lower for the two following cuts. Overall results of NFRV can be ranked according to: CAN ~BBFb ~UAN > CS +BBFb > CS.

Table 4 *Mean values with their standard error between brackets (SE[27]) for nitrogen fertiliser replacement value (NFRV) in percent (%) for CAN, BBF+/BBFb, CS and CS+BBF+/BBFb (1) per application rate for the total of all four (2020) or three cuts grass (2021) and three application rates. CAN serves as reference nitrogen fertiliser.*

Year	**Fertilising Product(1)**	**Application rate**		
		50%	**75%**	**100%**
2020	CAN	100 (6.7)	100 (1.2)	100 (1.6)
	UAN (2)	*	*	*
	BBFb	121 (6.9)	112 (9.3)	*
	CS	64 (4.7)	79 (7.7)	*
	CS+BBFb	*	81 (3.2)	74 (5.1)
2021	CAN	100 (3.5)	100 (22.1)	100 (6.7)
	UAN	78 (14.2)	72 (17.4)	*
	BBF+/BBFb	94 (4.0)	98 (16.8)	*
	CS	33 (8.7)	37 (17.2)	*
	CS+BBF+/BBFb	*	52 (15.6)	55 (5.4)
Average	CAN	100	100	100
	UAN	78 (14.2)	72 (17.4)	*
	BBFb	108	105	*
	CS	*	58	*
	CS+BBFb-(BBF+/BBFb)	*	76	78

(1) Fertilising products Cattle Slurry (CS), biobased fertiliser basic (BBFb), biobased fertiliser enriched with liquid ammonium sulphate and UAF (BBF+) applied for the first cut in 2021, biobased fertiliser enriched with UAF (BBFb) used in 2020 and for the second and third cut in 2021.

4.2.2.2 Silage maize

In 2019, two BBFs were tested: the enriched BBFa+ and the basic type BBFb. Also a diluted form of BBFa+ was tested (DBBFa+). In 2020, only biobased fertiliser basic (BBFb) was tested; a result of the observed ammonia toxicity in BBF produced with condensated ammonium water (at 6% proportion).

Dry matter yield and nitrogen uptake

Overall, effects of fertilising product or application rate on maize yield were not significant in 2019 or in 2020 (Figures 11 and 12). BBFa+ showed more variation in yield and nitrogen uptake than other treatments which is attributable to ammonia toxicity.

Nitrogen uptake increased with increasing application rates of nitrogen and, thus, was following the law of diminishing returns (Figures 11 and 12). Omitting nitrogen fertilisation resulted in significant lower nitrogen uptake. Highest nitrogen application rates (125%) occurred in 2020, with a significantly higher nitrogen uptake compared with the lower application rate (50%), but in general, nitrogen uptake did not differ significantly between fertilising products and application rates. Dry matter yields of non-fertilised plots did not differ from dry matter yields of treatments with N fertilisation, only nitrogen uptake was lower.

Overall, results of dry matter yields or nitrogen uptake at similar application rates had a clear ranking of application rates, taking into account the large variation (error bars). CS and combinations of CS + BBFb had similar yields and nitrogen uptakes compared to CAN, UAN or BBFb. This is an indication that the soil delivered ample nitrogen in both years.

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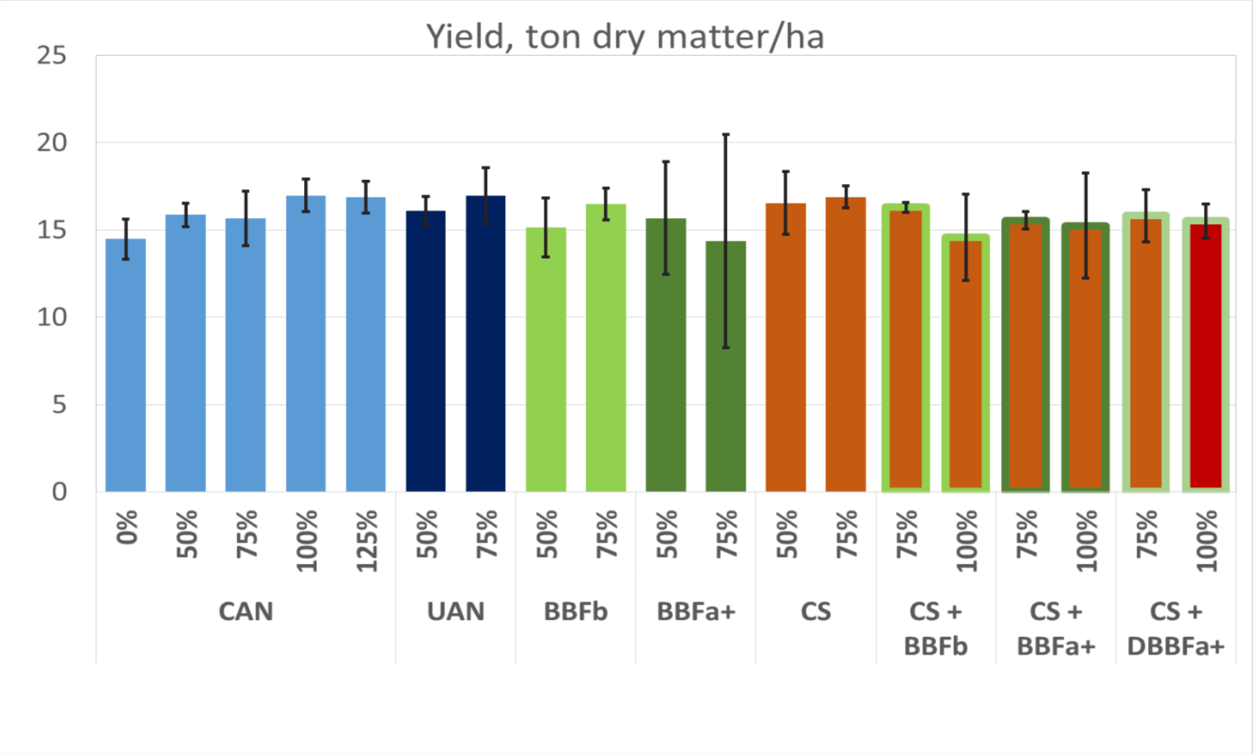
[27] Confidence interval can be estimated Mean value ± t x SE with a Student-t value 2.78 (n = 4).

NFRV
Dry matter yield of non-fertilised treatments (CAN 0%) yielded equal to fertilised treatments. In nitrogen uptake non-fertilised plot had lower values compared to with nitrogen fertilised values. From NUE, NFRV were derived (Table 5). NFRV for CAN were overall per application rate lower than BBFs, CS and combinations of CS+BBFs with exemption of BBFa+ and DBBFa+ and its combinations. Overall, NFRV ranked CS ~UAF ~ BBfb ~ CS+BBFb ~ CAN. Standard errors were large and through this, differences are often not significant. The application method of injection with placement of fertilising products near the seed of silage maize performed overall better than broadcasted prilled CAN.



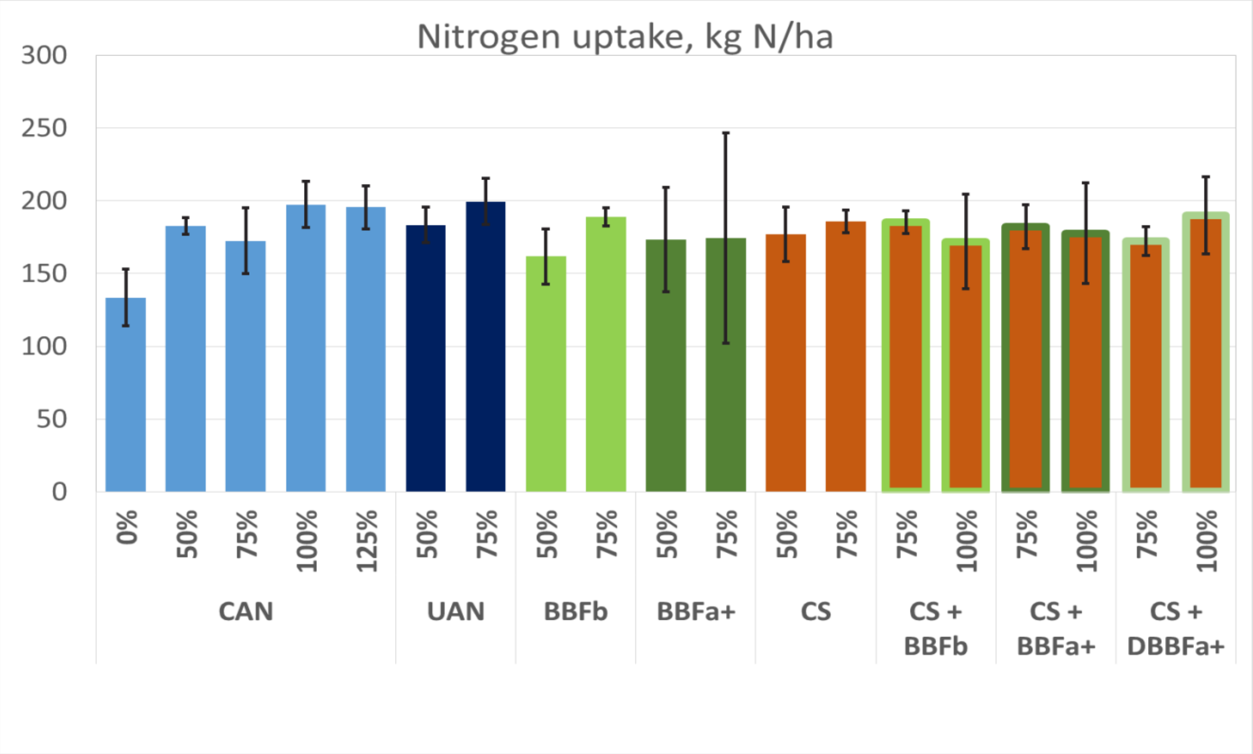
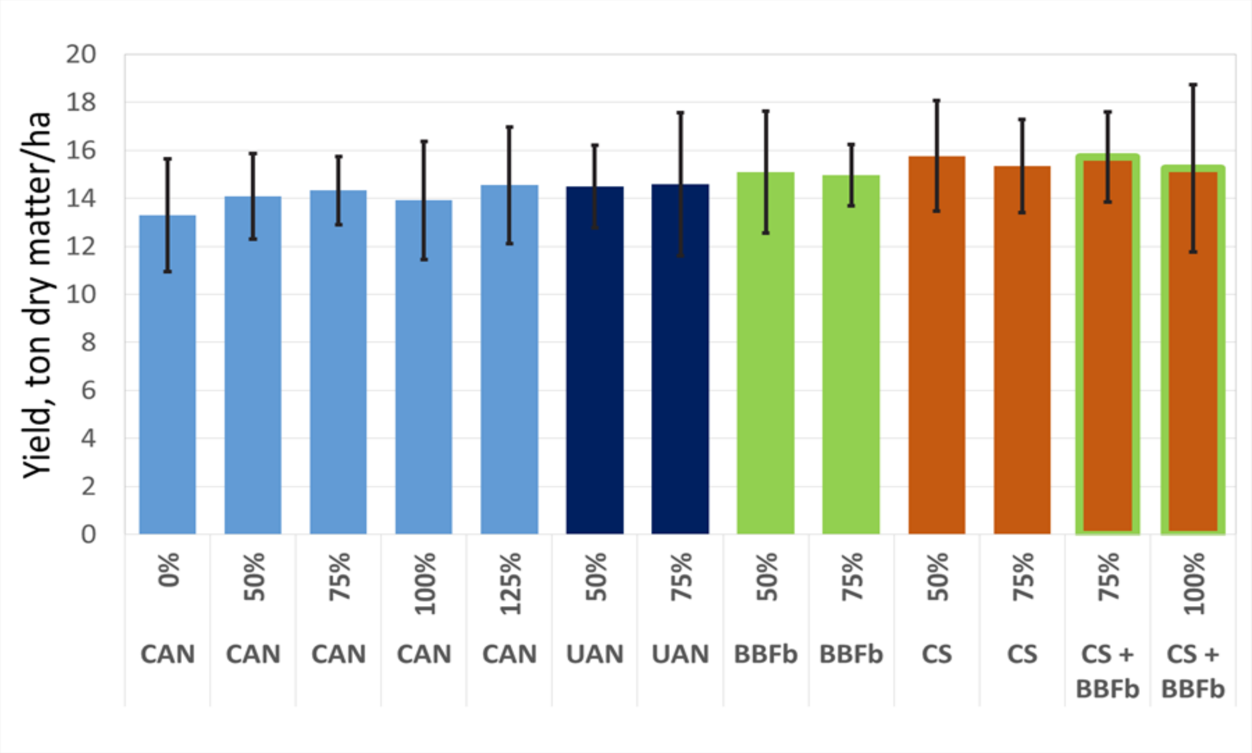


Figure 11 ***Above****: Yield of silage maize in ton dry matter/ha for 2019 for CAN, UAN, Biobased fertiliser basic (BBFb), enriched BBF (BBFa+), diluted BBFA+ (DBBFa+), Cattle Slurry (CS) and the combination with CS and BBFb, BBFa+ or DBBFa+ at application rates of nitrogen of 0%, 50%, 75%, 100% and 125%. Vertical bars represent standard deviations.* ***Below:*** *Nitrogen uptake by silage maize in kg N/ha for 2019 for CAN, UAN, Biobased fertiliser basic (BBFb), enriched BBF (BBFa+), diluted BBFA+ (DBBFa+), Cattle Slurry (CS) and the combination with CS and BBFb, BBFa+ or DBBFa+ at application rates of nitrogen of 0%, 50%, 75%, 100% and 125%. Vertical bars represent standard deviations.*



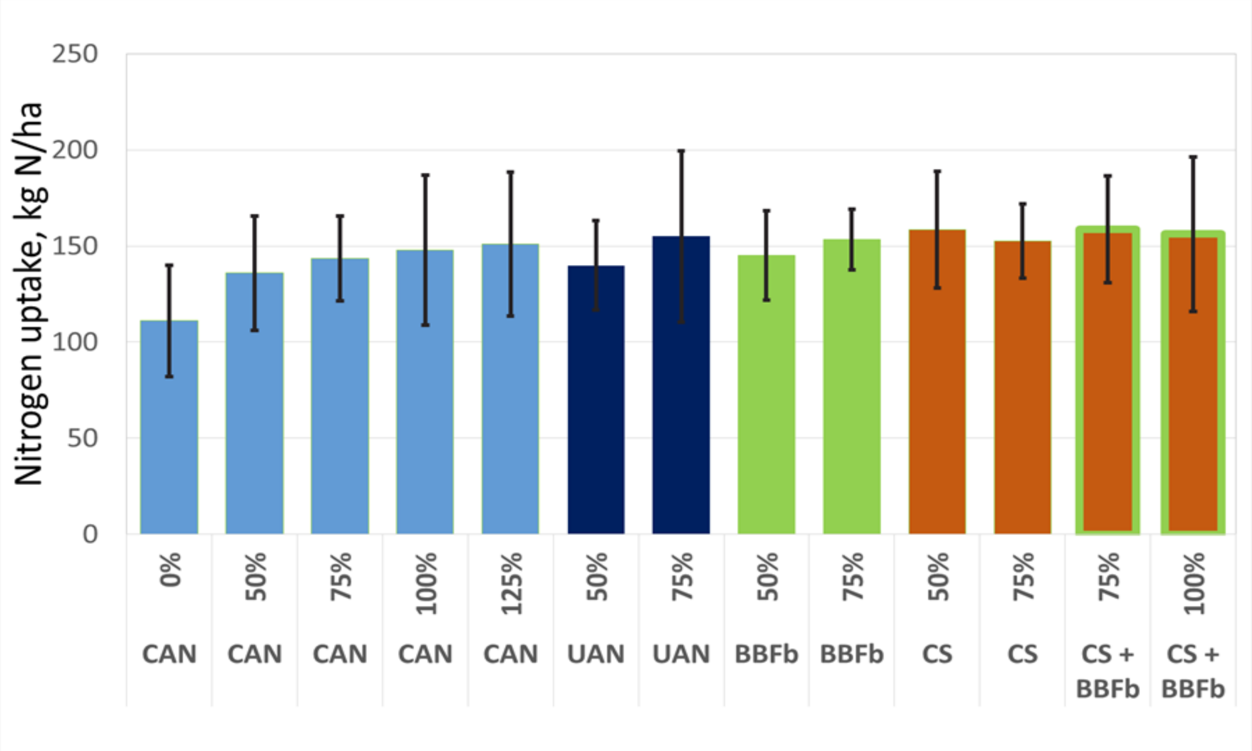


Figure 12 ***Above***: *Yield of silage maize in ton dry matter/ha for 2020 for CAN, UAN, Biobased fertiliser basic (BBFb), Cattle Slurry (CS) and the combination with CS and BBFb at application rates of nitrogen of 0%, 50%, 75%, 100% and 125%. Vertical bars represent standard deviations.* ***Below:*** *Nitrogen uptake by silage maize in kg N/ha for 2020 for CAN, UAN, Biobased fertiliser basic (BBFb), Cattle Slurry (CS) and the combination with CS and BBFb at application rates of nitrogen of 0%, 50%, 75%, 100% and 125%. Vertical bars represent standard deviations.*

Table 5 *Mean values with their standard error between brackets (SE[28]) for nitrogen fertiliser replacement value (NFRV) in percent (%) for CAN, BBFb, BBFa+, DBBFa+/CS and CS+BBFb for silage maize and three application rates. CAN serves as reference nitrogen fertiliser.*

Year	**Fertilising product**	**Application rate**		
		50%	**75%**	**100%**
2019	CAN	100 (14)	100 (12)	100 (12)
	UAN	126 (10)	128 (9)	*
	BBFb	74 (10)	115 (9)	*
	BBFa+	112 (10)	88 (9)	*
	CS	127 (10)	116 (9)	*
	CS+BBFb	*	113 (9)	64 (8)
	CS+BBFa+	*	107 (9)	75 (8)
	CS+DBBFa+	*	85 (9)	98 (8)
2020	CAN	100 (0.9)	100 (7.0)	100 (9.9)
	UAN	114 (9.1)	134 (12.6)	*
	BBFb	147 (6.5)	140 (11.2)	*
	CS	169 (9.3)	114 (11.3)	*
	CS+BBFb	*	154 (5.0)	114 (9.3)
Average	CAN	100	100	100
	UAN	120	131	*
	BBFb	111	128	*
	CS	148	115	*
	CS+BBFb	*	134	102
	BBFa+(1)	112	88	
	CS+BBFa+(1)	*	107	75
	CS+DBBFa+(1)	*	85	98

(1) Based on 2019, other values are based on 2019 and 2020.

4.2.3 Environmental risks

Environmental risks within the context of this Monitoring Program of WENR were focused on the risk on leaching of nitrate nitrogen. Actual leaching of nitrate was not measured, as this requires amongst others an in-depth monitoring of fluxes of water in soil and analyses of water samples from soil and soil pores over a prolonged period of time. As an alternative, the quantities (stocks) of mineral nitrogen in soil layers of depths 0 – 30 cm, 30 – 60 cm and 60 – 90 cm were measured before the start of the growing season and before fertilisation. This measurement was repeated after the harvest of the last cut of grass or the harvest of silage maize.

Based on measurements of applied fertilising product nitrogen, nitrogen uptake and stocks of mineral nitrogen at start and after the growing season, simple nitrogen balance sheets were calculated. The difference between the stock of soil mineral N after harvest and the sum of the quantity present at the start plus the N application rate minus the N uptake by silage maize is an indicator for the contribution by the soil. This is a simple form of a partial soil N balance sheet and ignores losses through ammonia volatilisation and denitrification.

4.2.3.1 Grassland

Environmental risks were assessed for the field experiment on grassland in 2020. An error in application of a biobased fertiliser based on ammonium sulphate instead of BBFb excluded sampling of the stocks of mineral nitrogen after the harvest in 2021.

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[28] Confidence interval can be estimated Mean value ± t x SE with a Student-t value 2.78 (n = 4).

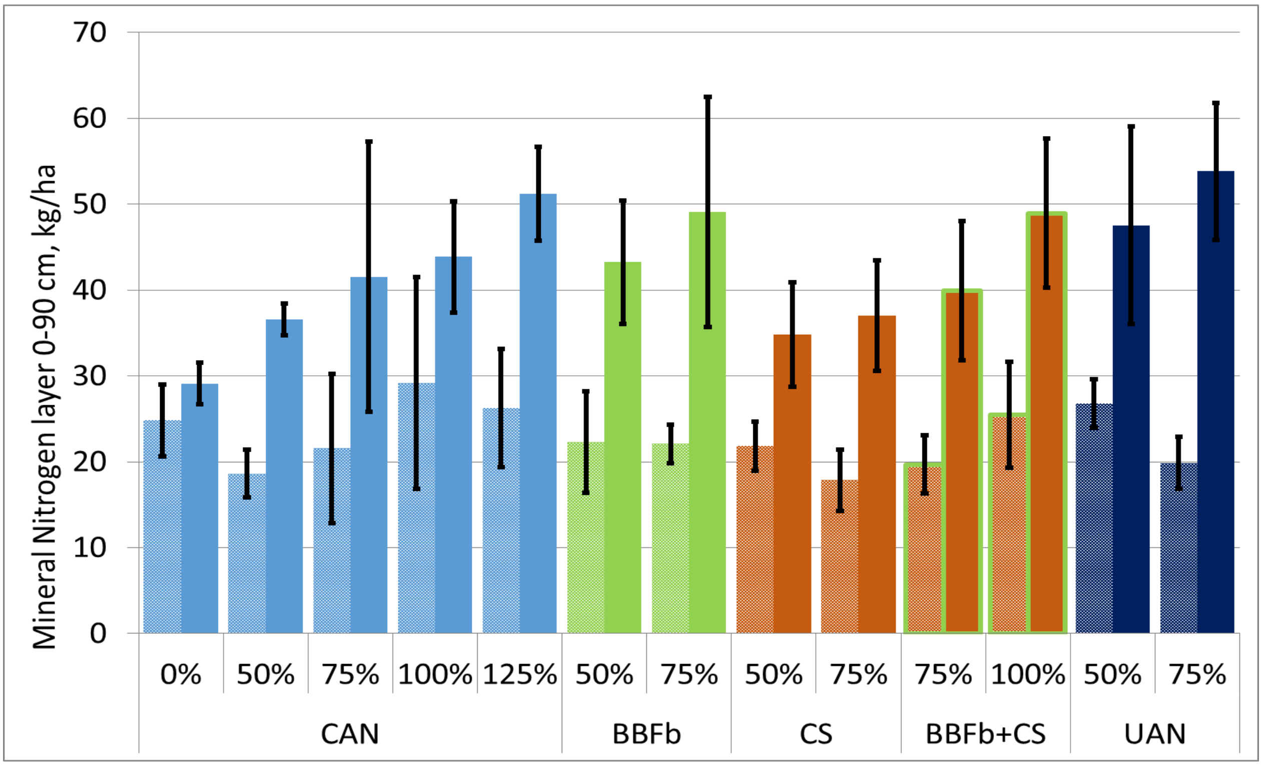

Figure 13 *Stocks of mineral nitrogen before fertilisation with nitrogen in March 2020 (dotted raster) and after the harvest of the last cut of grass in November 2020 (solid colouring) for CAN, UAN, BBFb, CS and the combination of CS + BBFb. UAN received for the first cut mistakenly also CAN.*

Fertilisation led to an increase of soils mineral nitrogen stock, but in general, differences between fertilising products were small (Figure 13).

The difference between the stock of soil mineral N after harvest and the quantity present at the start, plus the total N uptake by grass, minus the N application rate was used as an indicator for the contribution of nitrogen by the soil. Except for the treatment without nitrogen fertilisation (CAN 0%), all values are negative. With an increase of the application rate the values become more negative (data given by Ehlert et al., 2022b). However, mineral nitrogen stocks after the last cut of grass did not reflect an increase of mineral nitrogen in a comparable magnitude. A major part of the mineral nitrogen from fertilising products was not traced in the stocks of mineral nitrogen in the soil layer of depth 0-90 cm. Immobilisation in organically bound nitrogen most likely contributed to a lower nitrogen availability. Pathways for losses of applied mineral nitrogen were assumed to be:

- Volatilisation losses of ammonia.
- Losses through denitrification, and
- Leaching below the soil layer 0-90 cm.

Which pathway dominates, cannot be addressed with this research. Pathways will differ between fertilising products. Overall leaching was assumed not to be a major factor considering the dry growing period. The performance of the BBFb and CS injectors in minimizing ammonia volatilisation is not known but is assumed to be manageable i.e. small losses. Sprinkler irrigation might have stimulated mineralisation of organic matter and decomposition of grass roots under the warm weather conditions, and, thus, contributed to immobilisation. Sprinkler irrigation might have promoted denitrification.

4.2.3.2 Silage maize

Stocks in mineral nitrogen in the soil layer of depth 0 – 90 cm in 2019 and 2020 in Autumn after the harvest increased with increasing rates of nitrogen from fertilising products (Table 6).

2019

At the start of the field experiment during 2019, the soil layers of depths 0 – 30 cm, 30 – 60 cm and 60 – 90 cm had respectively 38, 13 and 3 kg/ha mineral N on average (Table 6). The total amount in the soil layer 0 – 90 cm was 54 kg N/ha. There were no significant differences in mineral soil N among the experimental plots.

After the harvest, soil mineral N was significantly different (α=0.05) between fertilising product treatments and application rates (Table 6).

Without N fertilisation (0 kg N/ha) the layer 0 – 30 cm and the layer 0 – 90 cm had a significantly lower quantity of mineral N after harvest in September than in April.

An application rate of 50% or 75% increased the quantity of soil mineral N measured in September for the UAN and BBFa+ treatments in the soil layer of depth 0 – 90 cm compared to the quantity measured in April (Table 6). For other fertiliser products the differences were not significant.

Application rates of 100% or 125% increased stocks of mineral soil N both compared to the stock in Spring as to the stocks after harvest for treatments with lower application rates.

Fields fertilised with BBFa+ had a similar of soil mineral N stock to fields fertilised with UAN at an application rate of 75%; both were significantly higher than CAN at the same application rate. BBFb, on the other hand, had significant less soil mineral N than BBFa+, CAN or UAN.

Application rates of CS or BBFb had no significant effect on soil mineral N.

At an optimal application rate of 100% the combinations of biobased fertilising products with CS had similar stocks of soil mineral N as CAN. There is, therefore, no evidence that the combined use exerts a higher risk on leaching of N.

2020

At the start of the field experiment in 2020, the soil layers of depths 0 – 30 cm, 30 – 60 cm and 60 – 90 cm had 19, 10 and 2 kg/ha mineral N on average, respectively (Table 6). The total amount in the soil layer of depth 0 – 90 cm was 31 kg N/ha. Within a treatment of a fertilising product some differences in soil mineral nitrogen at the start were found. On average however, there were no significant differences in the stock of mineral soil N among the fertilising products.

After the harvest, the stock of soil mineral N was significantly different between fertilising product treatments and application rates (Table 6). An increase in application rate of CAN resulted in an increase of the stock of soil mineral N; application rates of 0%, 100% and 125% were significantly different from each other. Without N fertilisation (0 kg N/ha) the soil layer of depth 0 – 30 cm and the soil layer of depth 0 – 90 cm had a significantly lower stock of mineral N after harvest in October than in April compared to 100% or 125%; the treatment of CAN 100% had a significant lower stock of mineral N compared to CAN 125%. For other application rates of CAN, a statistically significant difference was not found. Although the soils' stock of mineral nitrogen increased with an increase of application rate. Treatments with CAN and UAN tended to have a lower stock of mineral nitrogen in the soil layer of depth 0 – 90 cm compared to BBFb, CS and the combination CS+BBFb although not significant different. The treatment CS+BBFb 100% had a significant higher stock of soil mineral N higher compared to CAN 100% and UAN 100%. Other fertilising treatments were not significantly different. Application rates of UAN had no significant effect on soil mineral N.

Table 6 *Stock of mineral nitrogen in the soil layer of depth 0 – 90 cm at the start of the field experiments in Spring and after the harvest of silage maize in Autumn for CAN, UAN, BBFb, BBFa+, CS + BBFb, CS + BBFa+ and CS + DBBFa+. Data for BBFa+, CS + BBFa+ and CS + DBBFa+ are available for 2019 only.*

Fertilising product	**Application rate**	**2019**			**2020**		
		Spring	**Autumn**	**Difference Autumn - Spring**	**Spring**	**Autumn**	**Difference Autumn - Spring**
CAN	0%	54	28	-26	27	62	35
	50%	54	56	1	29	89	60
	75%	54	71	16	24	124	99
	100%	51	101	50	39	146	107
	125%	62	142	81	33	221	188
UAN	50%	65	67	2	30	107	77
	75%	52	103	51	29	101	72
BBFb	50%	56	40	-16	27	99	72
	75%	46	40	-5	41	156	115
BBFa+	50%	45	48	3	*	*	*
	75%	56	102	47	*	*	*
CS	50%	52	35	-17	37	83	46
	75%	53	51	-2	25	150	125
CS + BBFb	75%	56	38	-18	29	128	99
	100%	50	92	42	30	187	157
CS + BBFa+	75%	51	65	15	*	*	*
	100%	54	99	44	*	*	*
CS + DBBFa+	75%	50	45	-6	*	*	*
	100%	49	81	33	*	*	*
LSD (ɑ=0.05) Per sampling		12	23	*	7	40	*
LSD (ɑ=0.05) between samplings		21			41		

Stocks of mineral nitrogen in 2020 were larger than in 2019. Both field experiments were situated at the experimental farm, De Marke: both on sandy soil but on different sites. Both field experiments required sprinkler irrigation due to elevated temperatures and drought.

In both years, stocks of mineral nitrogen in the soil layer of depth 0 – 90 cm after harvest were lower than the application rates, which were targeted at 0, 93, 139, 186 and 232 kg N/ha. In 2019, these stocks were considerably lower than in 2020. In 2019, applied rates of N with BBFb and CS had no correlation to the stock of mineral nitrogen but applied rates of CAN and UAN had. In 2020, stocks of correlated with applied rates of nitrogen of all fertilising products. The years 2019 and 2020 differed in precipitation (Table 7). Both years had periods of drought and had a shortage of rain in the months April until July, but the shortage in the year 2020 was greater compared to 2019. A combination of drought and sprinkler irrigation in periods with less cover by the crop in 2020 and lower yields combined with lower N uptake is thought to be the cause for the differences in accumulation of mineral nitrogen in soil.

Table 7 *Monthly precipitation for 2019 and 2020 in mm and long-term averages (data from Experimental Farm De Marke).*

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
2019	51.2	76.8	75.2	25.3	28.2	34.6	19.0	72.2	60.6	74.0	82.1	53.6	652.8
2020	41.6	94.6	49.6	7.8	10.6	48.0	43.2	53.8	51.2	80.8	30.8	88.0	600.0
Long term monthly average	*70*	*58*	*67*	*42*	*62*	*68*	*78*	*78*	*78*	*83*	*82*	*80*	*846.0*

4.3 Evaluation, conclusion, and recommendations

Two field experiments on grassland and two field experiments with silage maize were conducted in the period 2019 – 2021. The experiments used the available biobased fertilisers. The composition of the BBFs changed during the time period due to innovative changes in the production process of the mineral concentrate at GMMC. In 2019, condensated ammonia water enriched fertilising product (BBFa+) and a diluted BBFa+ (DBBFa+) were included in the experiments. In 2019, the biobased fertiliser basic (BBFb) was produced with mineral concentrate and 1.5% condensated ammonia water. In 2020 and 2021, BBFb was produced from mineral concentrate and 1% UAN.

In 2020, storage of BBFb caused a decline in the nitrate nitrogen content. In 2021, the BBFb was made by blending mineral concentrate of GMMC and UAF at the actual fertilisation date. During fertilisation samples of the biobased fertiliser products and cattle slurry were taken for analysis. Actual applied rates of nitrogen are used for calculation of NUEs and NFRVs.

Field experiments of 2019 and 2020 had unfavourable weather conditions for crop growth, drought, and elevated temperatures. Sprinkler irrigation had to be used in these years to combat drought. The field experiment on grassland in 2021 had favourable weather conditions.

Grass responded well to nitrogen fertilisation, but silage maize showed no obvious, clear response. Variation within a treatment in 2020 was large, leading to non-significant differences for maize. These findings are thought to be caused by drought and the impact sprinkler irrigation had on mineralisation of organic soil nitrogen.

Overall, results of NFRV for grassland can be ranked according to: CAN ~ BBFb ~ UAN > CS +BBFb > CS, but a ranking for the testing of the fertiliser products with silage maize is not obvious.

On grassland, more nitrogen was applied than was traced in total nitrogen uptake by all cuts of grass and in residual soil nitrogen. Evidently, nitrogen is immobilized in the soil processes or lost by emission of ammonia or by denitrification (N_2O/N_2). After the harvest, the stock of mineral nitrogen and a similar application rate did not differ between BBFs or CAN.

Overall, the field experiments show that a BBF made from mineral concentrate and another nitrogen and/or sulphur source is similar in the agronomic effectivity when compared with CAN.

The environmental risk on leaching of nitrate nitrogen of GMMC’s BBFs is not different from those of CAN.

5 Evaluation, conclusions, and recommendations

WENR has supported the region Pilot Biobased Fertilisers Achterhoek with a Monitoring Program focused on desired product quality and product composition of fertilising products, and assessment of their agricultural effectiveness, and the associated environmental risk of nitrate leaching. The Monitoring Program consisted of five parts:

1. Assessment of risks associated with blending of fertilising products based on animal manure, sewage sludge, and mixtures of these.
2. Field experiments conducted in 2019, 2020 and 2021.
3. Demonstration field trials conducted in 2018, 2019 and 2020.
4. Annual technical reports on risk assessment, field experiments and demonstration trials.
5. Synthesis report of parts 1 – 4.

The Monitoring Program started in 2018 and ended in 2021. During this period, the aims of the Pilot were tuned to innovations at GMMC. Originally the aim was to produce BBFs that could meet criteria of the new European regulation on fertilising products (EC/2019/1009). The focus became the production of a mineral concentrate with low sulphur content. A production of a mineral concentrate with low sulphur content was realized in 2019, but had the concentration factor of the mineral concentrate from the liquid fraction of co-digested pig slurry was lower as a consequence. In this period, the Joint Research Centre proposed the RENURE criteria for nitrogen fertilising products produced from manure. The mineral concentrates of GMMC met these criteria (Regelink et al., 2021). In this Monitoring Program, BBFs of 2020 met the RENURE criteria and those of 2021 tend to have met the criteria for ratio of inorganic nitrogen to total nitrogen and ratio of organic carbon to total nitrogen. The factual assessment awaits the harmonized standard for analytical methods for assessing nitrogen forms (species) in BBFs. CEN[29] is currently working on these analytical standards.

The project started in the same timeframe that the Joint Research Centre (JRC) was carrying out its SAFEMANURE project from which the RENURE criteria were derived. The aim of the JRC project is the development of criteria for the safe use of processed N-containing fertilising products from manure in vulnerable zones (areas sensitive to nitrate leaching), established by the Nitrates Directive. The current project was triggered by the start of the SAFEMANURE project, but has another timeframe, as field experiments held in 2019 were also carried out in 2020 and 2021. The data and outcomes from this project serve as touchstones for the still to be implemented RENURE criteria for N fertilising products based on processed animal manure.

5.1 Risk of blending

Risks of the formation of nitrous oxide due to the addition of nitrate-containing fertilising products (AN) to mineral concentrate and risks of the formation of hydrogen sulphide due to the addition of sulphate-containing fertilising products to mineral concentrate were explored in two studies. The studies comprised of incubation of mixtures under standardized laboratory conditions.

Emission of N_2O was found after a lag-phase when AN was mixed with mineral concentrate. The conclusion is that adding nitrate to mineral concentrate from pig slurry leads to strong N_2O production. A proportion of an 8% addition did not lead to a higher degree of denitrification compared to a 4% proportion, but the process of denitrification was delayed.

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[29] CEN: European Committee for Standardization. CEN has the mandat of the European Commission for assessing harmonised standards for analyses of fertilising product designated by EC/2019/1009.

Loss of nitrate nitrogen was observed during storage of a batch of mineral concentrate (99%) and UAN (1%). This is also indicates that nitrate added to digestate is lost by denitrification as N_2 and N_2O.

Emissions of hydrogen sulfide were not observed when mixtures of ammonium sulfate solution with mineral concentrate produced from digestate were incubated. The technique for measuring this emission of hydrogen sulphide requires modification. New research has been designed to further investigate these emissions using a different measurement technique, but is not a part of this report of the Monitoring Program.

5.2 Demonstration fields

Demonstration fields enabled farmers to see the suitability of the BBFs for practical use. Two types of BBFs were tested consecutively; the first two cuts received with sulphur enriched BBF and following cuts a BBF not enriched with sulphur. The results of the agronomic effectivity and the environmental risk assessment were, thus, based on a combination of both types of BBFs. The agronomic effectivity was assessed by estimating yields based on measurement of grass heights. This form of determination of agronomic effectivity differs from the measurements and methods with field experiment (NUE and NFRV). For the demonstration fields, agronomic effectivity was derived from the relative yield estimates based on measuring grass height, which serves as an indicative qualitative parameter.

Demonstration fields were created with a simple design. Two treatments (BBF, blend of mineral synthetic nitrogen fertilisers) and one block without repetitions. The composition of the BBF and blend was tuned to crop requirements determined by soil testing for fertiliser recommendations. The basic concept was to produce BBF and blends with identical ratios of nitrogen, potassium and sulphur. Products of 2018, 2019 (partly) comply with this concept but partly in 2019 and 2020, there was a difference in the ratio (nitrogen/potassium and/or nitrogen/sulphur). Ten demonstration fields were conducted each year, these sites were repetitions, but differed in their fertilisation plans and grassland use. Next, the sites differed in options of sprinkler irrigation. Some farmers had the equipment, others did not. Lastly, sites differed per year. Ultimately, six sites received three years of monitoring. The number of sites with given differences and differences in composition of the BBFs during these three years limited detailed analysis of measurements focused on long-term effects of the use of BBF.

A treatment without nitrogen fertilisation was lacking. N uptake was not measured. Therefore, neither nutrient use efficiency nor nitrogen fertiliser replacement values could be derived from the results of demonstration fields.

All experimental years 2018, 2019 and 2020 were years with periods of severe drought in the Achterhoek region. Not all farmers were able to apply sprinkler irrigation. Drought hampered testing of fertilising products as drought became a main factor in crop development and not fertilisation. Drought lowered the effectivity of fertilisation.

The experience in 2018, 2019 and 2020 was that the agronomic performance of the biobased fertilising product approached the effectivity of the blend of mineral fertilisers in both yield and residual soil nitrogen after the last harvest provided that ammonia toxicity was avoided and the nitrogen application rate was based on measurement of the actual batch. Significant differences in agronomic performance between BBFs and the reference mineral fertiliser were not found due to the large variation.

During the monitoring it was recommended not to use condensated ammonia water. This secondary source of nitrogen is actually not used by GMMC anymore by. For steering of the quality of BBF an organised monitoring of the quality of GMMC was advised.

5.3 Field experiments

Two field experiments on grassland and two field experiments with silage maize were conducted in the period 2019 – 2021. The experiments used the available biobased fertilisers. The composition of the BBFs changed during the time period due to innovative changes in the production process of the mineral concentrate at GMMC. In 2019, a condensated ammonia water enriched fertilising product (BBFa+)

and a diluted BBFa+ (DBBFa+) were included in the experiments. In 2019, the biobased fertiliser basic (BBFb) was produced with mineral concentrate and 1.5% condensated ammonia water. In 2020 and 2021, BBFb was produces from mineral concentrate and 1% UAN.

Field experiments of 2019 and 2020 had unfavorable weather conditions, drought and elevated temperatures. Sprinkler irrigation was required in these years to combat drought. The field experiment on grassland in 2021 had favorable weather conditions.

Grass responded well on nitrogen fertilisation, but silage maize showed no obvious, clear response. Variation within a treatment in 2020 was large, leading to non-significant differences. These findings are thought to be caused by drought and the impact sprinkler irrigation had on mineralisation of organic soil nitrogen.

Overall, results of NFRV for grassland can be ranked according to: CAN ~ BBFb ~ UAN > CS +BBFb > CS, but a ranking for the testing of the fertiliser products with silage maize is not obvious. Actual applied rates of nitrogen are used for calculation of NUEs and NFRVs.

On grassland, more nitrogen was applied than was traced in total nitrogen uptake by all cuts of grass and in residual soil nitrogen. Evidently, mineral nitrogen is immobilised by soil processes (immobilisation) or lost through emission of ammonia or denitrification (N_2O/N_2). After the harvest, the stock of mineral nitrogen at a similar application rate did not differ between BBFs or CAN. On arable land (silage maize) mineralisation of soil organic nitrogen contributed to crops nutrition. Estimates for the quantity of mineralised organic nitrogen were of a similar magnitude of fertiliser application rates and are seen as cause for the poor response of silage maize on nitrogen fertilisation.

Overall, the field experiments have shown that a BBF made from mineral concentrate and another nitrogen and/or sulphur source is similar to the agronomic effectivity of CAN.

The environmental risks of BBFs of GMMC do not differ from those of CAN.

5.4 Conclusions and recommendations

Innovation at GMMC led to a continuous adjustment of production processes of mineral concentrates, which had an impact on its composition. Although the biobased fertiliser basic (BBFb) was used for all experimental years, the composition changed during these years. This is a condition that was taken into account when summarizing results.

Agronomic effectivity was assessed with different parameters. The results of the demonstration fields are based on estimates of relative yields based on measurement of grass height about 15 days after fertilisation and about 10 days before actual harvest. Results of with sulphur enriched BBFs used for fertilisation of the first two cuts and BBFb were grouped.

The results of the field experiment were based on measurements of yield and nitrogen uptake and are defined by NUE and NFRV per fertilising product.

Drought and elevated temperatures are not beneficial for grass growth (even with sprinkler irrigation) and causes effect on yield, nutrient uptake and soil processes that dominate fertilisation.

Provided that the constituent components are taken into account, the BBFs demonstrated a similar agricultural effectivity to a mineral nitrogen fertiliser. Use of condensated ammonia water (6%) lowered agronomic effectivity.

There are no indications that BBFs lead to a higher soil stock of mineral nitrogen compared to a mineral nitrogen fertiliser. Both have similar environmental risks on nitrate leaching.

Irrigation under elevated temperatures is assumed to have promoted mineralisation of organic nitrogen in the soil on arable land (silage maize) as nitrogen uptake of non-nitrogen fertilised plots was of comparable level as application rates of nitrogen. Also after the harvest an increase in mineral nitrogen in the soil layer of depth 0 – 90 cm was found.

On grassland nitrogen of fertilising products was not traced in soil mineral nitrogen of the soil layer of depth 0 – 90 cm. Immobilisation could have been a cause. The total uptake of nitrogen was lower than applied with the fertilising products but after the final harvest residual nitrogen from fertilising produced was not traced in similar quantities in soil. Pathways for losses of applied mineral nitrogen are assumed to have been:

- Volatilisation losses of ammonia.
- Losses through denitrification, and
- Leaching below the soil layer of depth 0-90 cm.

Based on the experiences from this Monitoring Program, the following recommendations are made:

- Standardise the ration of the digester of GMMC with a focus on a standardization of the composition of the resulting digestate of co-digested manure and resulting mineral concentrate.
- Support the production of BBFs with a guided sampling program on composition of digestate and mineral concentrate.
- Initiate additional research on risks on emissions caused by ammonia volatilization, denitrification (N_2O/N_2) or H_2S.
- Test new innovative BBFs with demonstration fields and field experiments.

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