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Agronomic performance of novel, nitrogen-rich biobased fertilizers across European field trial sites

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ABSTRACT

Context or problem: Substituting mineral fertilizers with novel biobased fertilizers (BBFs) produced from various organic waste and side streams could contribute to a reduction in the environmental and climate impacts of fertilizer production and use and the recycling of otherwise potentially wasted nutrients. For the substitution to be beneficial for farmers, the environment, and food security, the BBFs need to be effective, reliable and safe. However, the agronomic performance of novel, nitrogen (N) rich BBFs has not yet been well studied.
Objectives or research question: The main objective of this study was to determine the agronomic efficiency of N in a relevant range of commercially available BBFs. We hypothesised that they can function as effective substitutes for mineral N fertilizers, independent of the agricultural and geographic settings.
Methods: Field trials (fully randomized block design) were conducted at four field sites across Europe covering different climates, soil types, and crop sequences. In total 18 BBFs were tested, 7 of which were common BBFs tested at all sites, while the other 11 (2–3 per site) were local BBFs at individual sites. The design included 4–5 increasing levels of mineral N reference. Trials with BBF application were conducted over 2 years, and the agronomic performance (crop yield and N offtake) was determined to estimate 1st year mineral N fertilizer replacement value (NFRV) in both years, while residual NFRV was estimated only in the 2nd year.
Results: The BBFs showed an average N fertilizer replacement value (NFRV) of 70 % across sites and years, with variations in the agronomic performance between the trial sites and years. Compared with the mineral N fertilizer reference applied at the same total N level, no consistent ranking of BBF and no significant differences in yields were found. The BBFs tended to have a higher NFRV when incorporated compared to surface application. Of the 18 BBFs tested, 8 had a NFRV above 75 %, 6 were in the range 60–75 % and 4 were in the low range of 10–60 %. The residual effect of BBFs in the year after application was not significantly higher for any of the BBFs than that of the mineral N fertilizer.
Conclusions: Generally, the BBFs performed similar to the mineral reference applied at the same total N level. The performance of BBFs was not significantly affected by climate or soil type. The BBFs appeared to have higher agronomic performance when incorporated into the soil compared to surface application. The second year residual effect of BBF was not significantly higher than that of the mineral reference fertilizer.
Implications or significance: In general, most of the investigated BBFs can be considered reasonably effective substitutes for mineral N fertilizers. The results suggest that soil incorporation of BBFs will result in better agronomic performance than surface application.

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1. Introduction

The United Nations project that the earth's population will grow to 9.7 billion by 2050 (United Nations., 2022). To feed the increasing human population, future food production needs to be more efficient and less harmful to the environment. This can be achieved by changing to more plant-based diets, expanding cultivated areas or increasing the productivity of existing agricultural land, e.g., by applying higher amounts of fertilizers (Tilman et al., 2011). Since the invention of the Haber-Bosch technology to produce mineral N fertilizers, use of and dependency on mineral fertilizers has increased, as have crop yields. However, the production of mineral N fertilizers through Haber-Bosch synthesis is very energy-intensive (Sigurnjak et al., 2017; Svanbäck et al., 2019), resulting in a high climate impact as the energy sources used are mainly based on fossil fuels. Moreover, current highly fluctuating energy (gas) prices have led to increased price volatility for mineral N fertilizers (Schnitkey et al., 2023).

One way to substitute mineral N fertilizers could be to reuse otherwise poorly utilized organic materials to produce biobased fertilizers (BBFs). BBFs have been defined by (Wester-Larsen et al., 2022) as "materials or products derived from biomaterials (plant, animal, or microbial origin, often wastes, residues, or side-streams from agriculture, industry, or society) with a content of bioavailable plant nutrients suitable to serve as a fertilizer for crops". The recovery of nutrients from organic wastes is a central part of the European Commissions's bioeconomy strategy. As part of the transition towards optimal use of resources, the European Union aims to make greater use of recycled organic resources to satisfy consumer and industrial demands, thus mitigating climate change and combating the depletion of non-renewable rock phosphate. The European Commission's "Europe 2020" strategy to develop a sustainable low-carbon economy by 2050 (EC, 2011) regards the substitution of mineral fertilizers in agricultural production with BBFs an important pathway for the recovery of materials and energy (Christel et al., 2014).

Due to their novelty, little is known about the fertilizing efficiency of novel BBFs and their potential to replace Haber-Bosch synthesized mineral N fertilizers (Sigurnjak et al., 2019; Vaneeckhaute et al., 2014). Biobased fertilizers with high organic N contents could be used as single-application N fertilizers. Due to their organic composition, the release of nitrogen depends on microbial decomposition, which is affected by soil moisture and soil temperature (Abbott et al., 2018). Thus, BBFs, where parts of the N content is organic, may act as slow-release fertilizers, providing adequate nutrients for the crop during the growing season (Chae and Tabatabai, 1986; Nardi et al., 2018). However, if the nutrients do not become available until after the crop has stopped taking up nutrients, this may lead to a reduction in yield and potential loss of these nutrients, if no other crop is there to take them up. If this delay in nutrient availability is sufficiently long, the nutrients applied with BBFs could be available for subsequent crops, i.e., BBFs could have a residual fertilizing value. Moreover, variations in BBF fertilizer efficiency are to be expected between European sites with varying climates and soil types. With the hitherto inconsistent European legislative systems regulating BBFs (Vaneeckhaute et. al., 2014), the new European Union (EU) fertilizing product regulation (EU, 2019) aims to make BBFs enter the European fertilizer market on equal terms with mineral fertilizers. Therefore, it is necessary to investigate novel BBFs in different European settings to generate knowledge on the efficiency of BBFs and their potential to replace mineral fertilizers.

The overall objective of this study was to determine the agronomic efficiency of a relevant range of commercially available BBFs. The specific objectives were to: i) determine their mineral N fertilizer replacement value; ii) examine the impact of agricultural (crop) and geographic (soil type and climate) setting on their agronomic efficiencies; and iii) determine their second-year residual fertilizing effect.

The following hypotheses were tested: i) BBFs can function as substitutes for mineral N fertilizers; ii) BBFs have a second-year residual fertilizing effect significantly above that of mineral N fertilizers; and iii) the agronomic efficiency of individual BBFs varies with agricultural and geographic setting.

2. Materials and methods

2.1. Sites and soils

The Field experimental data in this study originate from four field sites, but originally five sites across a climate gradient in Europe from Spain (Seville) and France (Toulouse) in the south, Germany (Stuttgart) in the centre, to Denmark (Copenhagen) and Finland (Forssa) in the north were included. Thus, covering Mediterranean (Spain), Atlantic (France), Continental (Germany and Denmark) and Boreal (Finland) biogeographical regions (EEA, 2017). The trials in Spain however failed in both years due to drought and data is therefore not reported in this paper (see 2.4.3), why soil data for Spain is omitted from Table 1. To ensure a response to N fertilization, sites were selected based on certain criteria: no organic fertilizer application five years prior to the start of the experiment and no N-rich (leguminous) crops or cover crops included in the previous crop rotation. Soil samples were collected prior to the start of the experiment to determine soil properties (Table 1).

2.2. Weather data

Monthly average temperature and monthly sum of precipitation were obtained from the nearest weather station for each site for the two experimental years 2021 (Fig. 1A) and 2022 (Fig. 1B). Climate norms (average of last 30 years) were acquired from climate-data.org and values were subtracted from the 2021 and 2022 values to display the monthly deviations from the climate norm for each site for these years (Fig. 1C and D).

2.3. Biobased fertilizers

All the BBFs investigated in the current study were commercially available on European or regional/national markets at the time the experiments were conducted. Seven of the BBFs tested in this study were available across Europe as pellets or granules and tested in each trial site. These seven "common" BBFs were taken from a list of 39 (Wester-Larsen et al., 2022) and selected to represent the variation in BBFs on the list in terms of source materials and processing technology. Another selection criterion was that they had a high technology readiness level, and were available in sufficiently large quantities in Europe (Bauerle et al., 2021). Partners at each site selected, additionally to the seven common BBFs, two to three BBFs that were of local (national, regional)

Table 1
Coordinates and soil properties of the four sites (France, Germany, Denmark and Finland). See supplementary material for description of methods used for soil analysis.

	France	Germany	Denmark	Finland
Latitude N	43.492826	48.715024	55.674204	60.804564
Longitude E	1.202851	9.2144937	12.287907	23.454594
WRB soil type	Luvisol	Haplic Luvisol	Arenosol	Vertic Cambisol
Clay % (<0.002 mm)	17	30	6.2	45
Silt % (0.002–0.02 mm)	26	68	5.5	25
Sand % (>0.02 mm)	57	2	85.3	30
Organic C (g kg^{-1})	9.2	14	15	26
pH H_2O	7.38	6.99	6.01	6.60
Olsen P (mg kg^{-1})	23	-	34	72
CAL-P (mg kg^{-1})	-	15.5	-	-
Exchangeable K (mg kg^{-1})	128	-	103	208
CAL-K (mg kg^{-1})	-	20	-	-

relevance and interest in terms of either traditional fertilizer distribution logistics, availability on regional markets or their physical form (e.g. liquid/moist) impeding long distance transport (Table 2). Because the BBFs ranged from liquid, semi-liquid to pelletized BBFs the fertilizer application technique was also correspondingly different.

2.4. *Trial design*

The field trials were established at each site using a complete randomized block design, except for Finland where a row-column design was used. All trial fields were designed with 4 replicates (blocks) of all treatments. Individual plot sizes varied from 30 to 150 m^2 among the sites.

The trials were conducted during two cropping seasons (2021 and 2022) as two separate one-year trials. In 2021, spring crops were grown at all sites (Table 3). In 2022, winter crops were grown at all sites, except in Finland (spring crop) where spring cereals are more common due to climatic limitations for winter types. BBFs were incorporated for spring-sown crops and surface-applied in spring in the growing crop for autumn-sown crops. The first-year fertilization effect was evaluated for 2021 in one area of the field, and in 2022 in another area adjacent to the first area, except in Finland where the two trials were conducted in different fields 600 m apart. In 2022, the residual effect of the 2021 fertilization was determined in the area fertilized in 2021, without additional fertilization in 2022. Additionally, at the German site in 2023, the residual fertilization effect of the 2022 fertilization was determined in the area fertilized in 2022, without additional fertilization in 2023.

The trials were designed and run under a commonly agreed and detailed internal project field trial protocol, to ensure comparability across trial sites but with local fertilizing recommendations and common cropping practices of each country. Therefore trial design and plot sizes varied slightly among the trial sites. Table 3 lists the crops grown, the total BBF N quantity applied, the application method used, and the mineral N reference application levels for all trial sites and years.

2.4.1. *Fertilizer management*

The BBFs were applied based on total BBF N content at the level recommended by local advisory services and based on experience for the specific crops each year (Table 3). The fertilizers were all applied on the same day, or in two days, in the spring prior to sowing for the spring-sown crops and at the onset of crop spring growth for autumn-sown crops. The BBFs were applied in a manner as close to common farming practice as possible, e.g., in strips simulating a trailing hose for liquid BBFs and broadcast applied for solid pelletized BBFs. For spring-sown crops, BBFs were incorporated to a depth of 10 cm within 24 hours of application, shortly before sowing of the crop. For autumn-sown crops, BBFs were surface-applied in the spring in the growing crop. The sites were fertilized with sufficient amounts of all other nutrients, other than N (phosphorus (P), potash (K), sulfur etc.) in easily available mineral fertilizers, according to local common practice, to ensure that only N was growth-limiting.

Mineral N fertilizer (ammonium-nitrate based, since this is the most common mineral N fertilizer form used in European) was applied at four to five gradually ascending levels with the lowest at zero and the highest slightly above the level at which the BBFs were applied (Table 3). Exceptions to this rule were made in France and Finland, where the second-highest reference received the same amount of N as the BBFs (at all other sites, it was lower). In Finland, another exception was a 6th reference (Fig. S1), which was used for fitting equations for the references (2.5) but left out for further evaluations made in this study for comparability reasons. In Germany, it is common practice to take the initially measured soil mineral N content into account when calculating the fertilizer application amount; therefore this was done for the German site, but not for any of the other sites.

The BBFs were applied on different dates depending on the site and year (Table 3). At the Danish site, the application of the mineral references was split into two doses for winter wheat in 2022, as this is common practice. The second dose of mineral references was applied on 2 May 2022. However, the BBFs were all applied at one time and in one dose. At the French site, the application of the mineral references was split into three doses for winter wheat in 2022, as this is common

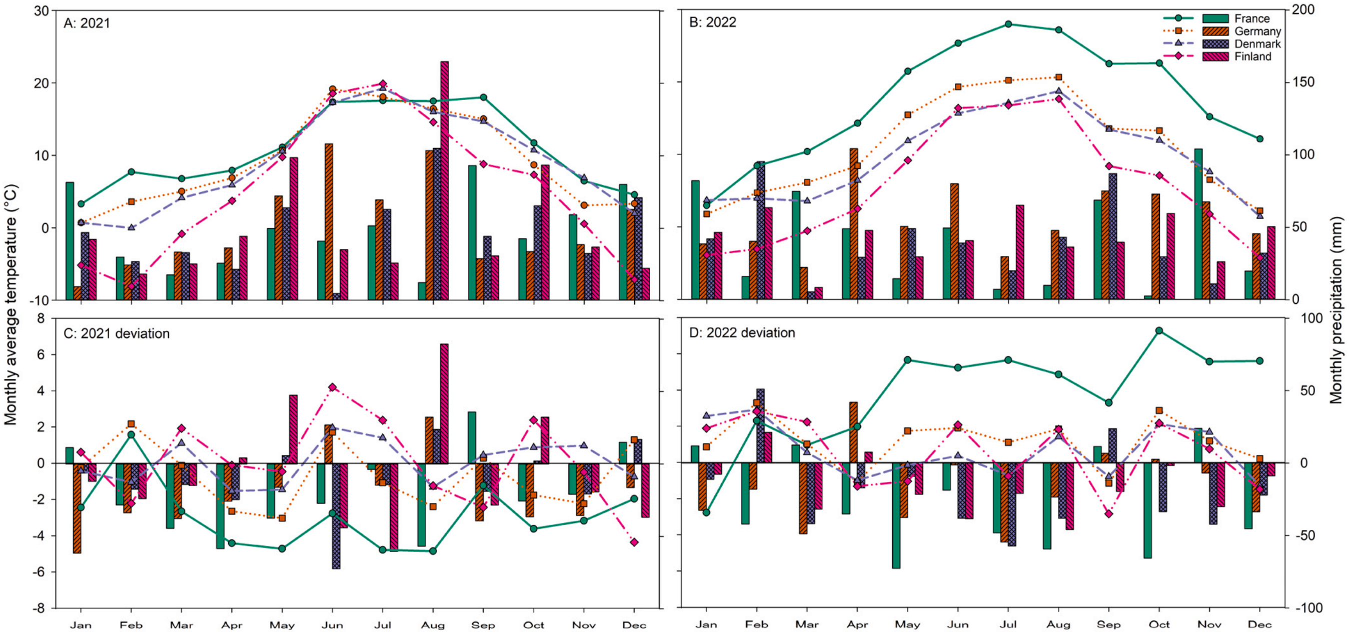

Fig. 1. Weather data from weather stations at the experimental field sites (France, Germany, Denmark, and Finland) for 2021 and 2022 (A and B). C and D show the deviation of the 2021 and 2022 weather data from the long-term mean at the respective location (France: Toulouse 1991–2021, Germany: Stuttgart 1999–2019, Denmark: Taastrup 1999–2019, and Finland: Forssa 1991–2021) (climate-data.org). Negative values demonstrate colder or drier months compared to the climate norm, positive values demonstrate warmer or wetter months compared to the climate norm. The monthly average temperature (°C) is displayed as points (left axis) and the sum of monthly precipitation (mm) as columns (right axis).

Table 2
Biobased fertilizer (BBF) component(s) and properties; pH (1:5 in Milli-Q water), total N, NH_4^+-N, NO_3^--N, dry matter (DM) content, total C, and C:N ratio. N and C are reported as % of fresh weight (FW). Values are means, *n*=2, except for C and N of liquid BBFs where *n*=5 and pH where *n*=3. The BBFs are presented here by acronym, with local BBFs in italics. Full product names and list of manufacturers can be found in the supplementary material (Table S1). The data is derived from Wester-Larsen et al. (2022).

	BBF Treatments	**Component(s)**	**pH**	**N** (% of FW)	**NH_4^+-N** (% of total N)	**NO_3^-N** (% of total N)	**DM** (g kg^{-1} of FW)	**C** (% of FW)	**C/N**	**P** (% of FW)	**N/P**	**K** (% of FW) **	**N/K**
Common	BA6	Fermented and distilled plant-based residues	4.85	5.57	1.4	<0.1	907	43.6	7.83	1.23	4.53	1.3	4.29
	BIO	Pelletized meat and bone meal, apatite, vinasse, poultry manure, and potassium sulfate	5.69	7.39	3.5	<0.1	941	35.9	4.85	4	1.85	2	3.7
	ECO	Pelletized blood and feather meal	5.48	11.6	2.7	<0.1	892	45.3	3.89	0	-	0	-
	FEK	Pelletized poultry manure	6.43	3.94	20	<0.1	901	34.7	8.81	1.3	3.03	1.99	2.42
	MO13	Pelletized feather meal	5.07	14.2	1.0	<0.1	927	49.0	3.45	0.2	64.5	0	-
	OG2	Hydrolyzed horn meal (pig bristles)	5.29	13.9	1.0	<0.1	940	48.3	3.47	0.3	46.4	0.01	>1000
	PAL	Fermented biochar and high-quality clay and rock flour	5.55	4.89	19	0.1	907	38.8	7.92	0.87	5.67	4.98	0.98
France	*FR13*	Pelletized sterilized feather and pig bristle powders	5.74	11.9	3.45	<0.1	901	45.3	3.8	0**	-	0	-
	FR8	Pelletized sterilized animal proteins, bone powders, feather and pig bristle powders	6.30	7.67	3.17	<0.1	946	34.2	4.5	10	0.77	4.1	1.86
Germany	*ASL**	Product of nutrient recovery plant. Ammonium sulfate (liquid)	7.42	4.76	100	<0.1	216	0.11	0.02	0	-	0	-
	GRF	Anaerobically digested manure and crops	8.19	0.37	75	0.3	45	2.02	5.46	0.1	7.24	0.41	0.90
	MAL	Pelletized malt germ and minerals, and vinasse	5.02	4.37	28	<0.1	955	35.0	8.02	0.4	1.93	4.1	1.07
Denmark	*BVC*	Anaerobically digested and composted municipal organic food waste	8.56	1.57	8.1	<0.1	557	14.7	9.37	0.77**	2.04	0.53	2.96
	PCW	Potato cell water	4.70	1.53	15	1.1	339	11.2	7.29	0.4	3.83	6.5	0.24
	SDG	Anaerobically digested agro and food waste + seaweed	8.40	0.41	68	<0.1	38	1.08	2.63	0.06**	6.83	0.11	3.37
Finland	*AV8*	Pelletized poultry manure, blood meal, and potassium sulfate	6.51	7.24	8.4	<0.1	920	38.9	5.38	1	7.24	0	-
	BO4	Anaerobically digested vinasse	6.23	3.56	1.3	0.6	620	21.2	5.96	0	-	7.8	0.46
	FEL	Pelletized poultry manure	6.70	4.51	3.3	<0.1	925	36.0	7.98	1	4.51	2	2.26

* ASL was applied in two different ways; ASL1 same as all other BBF, ASL2 was directly injected in the soil in both years. Data marked with † is information obtained from the BBF producers.

Table 3
Type of mineral fertilizer used as reference at the four sites. Total N applied for BBFs and mineral references in the categorized reference groups (Ref_1 – Ref_5) for each site and crop. The second lowest references at the Finnish site (30 kg N ha^{-1} in 2021 and 25 kg N ha^{-1} in 2022) were left out of statistical analysis and are not shown in the table. Application method used and crops grown at each site and year.

Year	**2021**				**2022**			
Trial site	France	Germany	Denmark	Finland	France	Germany	Denmark	Finland
Crop	Corn maize	Silage maize	Spring barley	Spring barley	Winter wheat	Winter wheat	Winter wheat	Spring wheat¶
Mineral Reference	AN †	CAN ‡	AN §	AN *	AN †	CAN ‡	AN §	AN *
Applic. Method	Incor-porated	Incor-porated	Incor-porated	Incor-porated	Surface applied	Surface applied	Surface applied	Incor-porated
Date of BBF application	6/4	26/3–28/3	29/3	24/5–25/5	7/2	1/3–2/3	30/3	19/5
BBF application (kg N ha^{-1})	**200**	**116**	**137**	**90**	**200**	**160**	**181**	**100**
Ref_1 (kg N ha^{-1})	0	0	0	0	0	0	0	0
Ref_2 (kg N ha^{-1})	-	33	-	30	-	45	-	50
Ref_3 (kg N ha^{-1})	100	66	50	70	75	90	70	75
Ref_4 (kg N ha^{-1})	200	99	100	90	150	135	140	100
Ref_5 (kg N ha^{-1})	250	132	150	110	225	180	210	125

AN: Ammonium nitrate; CAN: Calcium ammonium nitrate. †16.8 % NH_4^+-N, 16.7 % NO_3^-N; ‡13.5 % NH_4^+-N 13.5 % NO_3^--N, 12 % CaO, 4 % MgO; § 13.5 % NO_3^--N, 13.5 % NH_4^+-N, 3.7 % S, 0.6 % MgO; * 14.6 % NH_4^+-N, 12.2 % NO_3^--N, 1 % K_2O, 4 % S.

practice.

2.4.2. Crop management

Crops were mainly harvested using an experimental combine harvester on a representative area varying in size from 15 to 25 m^2 (depending on site) for each treatment. At the German site, maize (2021) and wheat straw (2022) were harvested by hand while wheat grain yield was determined using a combine. The dry matter of grain and straw was determined by drying the samples at max 65 °C for three days. Grain yield at 15 % moisture was calculated. The total N and C contents of straw and grain, or whole crop (silage maize), samples were determined using an elemental analyser (France, Germany and Denmark). At the Finnish site, grain N was determined using near infrared spectroscopy calibrated with Kjeldahl N measurements and with Kjeldahl N measurements for straw N content. The crop N offtake was calculated as the sum of the grain and the straw N content (dry matter x N concentration) per ha.

2.4.3. Site-specific adaptations to external effects

At the Spanish site, extreme drought led to failure of the experiment in both 2021 and 2022, since irrigation was not available at the site and not common practice in the area. Therefore, the data was not included in this study. At the Finnish site in 2021, heavy rain immediately after sowing and a following one-month drought period led to the failure of seed emergence and to total yield loss. Therefore, only the first-year fertilization effect of 2022 and the residual fertilization effect of the 2021 trial were included in this study for this site. However, no data for straw N offtake was collected for the second-year residual fertilization trial for the Finnish site. Due to transportation issues during the COVID-19 pandemic, the BBF 'PAL' (Table 2) arrived too late to be included in the Danish trial in 2021. It was therefore only included in the 2022 trial here. At the German site, fertilization with 'GRF' (Table 2) in 2021 was unsuccessful due to technical problems and this treatment was thus excluded in the first year. At the French site, the fields were irrigated both years.

2.5. Calculations of mineral fertilizer equivalent values

The grain yield (DM), or aboveground biomass for silage maize, of the mineral references was plotted as a function of the application rate and linear equations of 2nd-order and 3rd-order were fitted to the points. The R^2 values of the fitted equations were assessed and the equation with the highest R^2 value was chosen. In all cases, a 2nd-order equation was chosen (Table S3). The equation was then used to calculate the yield at the level of BBF N application. Then the mean grain yield (DM) of the unfertilized reference (REF1) and the grain yield (DM) for the mineral reference at the BBF application level (REF) were plotted and the slope of the linear regression line between these points was used as the agronomic efficiency (AE) of the mineral reference. The AE of each BBF replicate was calculated using Eq. 1.

$$\mathrm{BBF_{AE}} = \frac{\mathrm{Yield_{BBF_x}} - \mathrm{Yield_{REF_1}}}{\mathrm{N\ applied_{BBF_x}}} \tag{1}$$

Subsequently, the N fertilizer replacement value (NFRV) based on AE was calculated using Eq. 2:

$$\mathrm{BBF}_X\mathrm{NFRV_{AE}} \quad (\%) = \left(\frac{\mathrm{AE_{BBFx}}}{\mathrm{AE_{REF}}}\right) * \quad (100) \tag{2}$$

Likewise, the calculation of NFRV based on N use efficiency (NUE) was performed in the same way as for $\mathrm{NFRV_{AE}}$ where the crop N offtake (grain and straw) was used instead of grain yield and linear equations were fitted to the mineral N references. The equations used, and R^2 values are provided in the supplementary material (Tables S2 and S3).

2.6. Statistics

Data were split into trials fertilized in the current year and trials fertilized in the year prior to data sampling (residual value). In both cases, data were analyzed using a two-stage analysis, where means and their standard error were estimated per location and year first and then subjected to the across-location and across-year analysis in the second stage (Möhring and Piepho et al., 2009). In the first stage, trials were analyzed according to the randomized complete block design used in the trials in Denmark, Germany, and France by

$$y_{ij} = \mu + \tau_i + \varphi_j + e_{ij} \quad ,$$

where y_{ij} is the observation of fertilization treatment i in block j, μ is the intercept, τ_i is the fixed effect of treatment i, φ_j is the random effect of block j, and e_{ij} is the confounded effect of plot effect and error of y_{ij}. In Finland, a non-resolvable row-column design was used, therefore data were analyzed by:

$$y_{ijk} = \mu + \tau_i + \varphi_j + \quad f_k + e_{ijk} \quad ,$$

where y_{ijk} is the observation of fertilization treatment i in block j and column k, μ is the intercept, τ_i is the fixed effect of treatment i, φ_j is the random effect of block j, f_k is the random effect of column k, and e_{ijk} is the compounded effect of plot effect and error of y_{ijk}. Afterwards, treatment means $\bar{y}_i$ of location m in year l were used in the second-stage model given by:

$$\bar{y}_{ilm} = \mu + \tau_i + a_l + \quad l_m + (al)_{lm} + (\tau a)_{il} + (\tau l)_{im} + (\tau al)_{ilm} + f_{ilm}$$

where y_{ilm} is the observation of treatment i at the mth trial site of year l, μ is the intercept, τ_i is the fixed effect of treatment i, l_m is the fixed effect of location m, a_l is the fixed effect of year l, $(al)_{lm}$ is the random effect of the trial in location m and year l, $(\tau l)_{im}$ is the fixed interaction effect of treatment i and location m, $(\tau a)_{il}$ is the random interaction effect of treatment i and year l, $(\tau al)_{ilm}$ is the random interaction effect of treatment i with year l and location m, and f_{ilm} is the approximated error of mean $\bar{y}_{ilm}$. The errors of $\bar{y}_{ilm}$were approximated with the diagonal element of the R matrix fitted in stage I.

The model was extended by accounting for the application method. Note that all trials in 2021 used the application method 'incorporated', while in 2022 fertilizers were surface applied in France, Germany, and Denmark, but again incorporated in Finland (Table 3). Therefore, application methods and year can be separated, but their interactions with locations were confounded. Arbitrary, year-by-location and year-by-location-by-treatment effects were fitted, but the effects estimate the confounded effect. Note further that crop and year effects were also confounded. Again, year effects and their interaction effects were completely confounded with the corresponding crop effects.

Pre-requirements for analysis (normal distribution and homogeneous variances of residuals) were checked graphically via residual plots. Where significant differences were found for one term, corresponding least square means were compared using Fisher's LSD test. A letter display was used for description of results of multiple comparisons. For the statistical analysis, the program SAS 9.4 TS Level 1M7 was used. For graphical work, SigmaPlot 14.0, Systat, was used.

3. Results

3.1. Agronomic performance of novel BBFs

3.1.1. First-year effect of BBFs

Fertilization with BBFs and mineral fertilizers had a significant impact on yield at all sites in both years (Table 4). In 2021, fertilization with BBFs and mineral fertilizers had no significant effect on N offtake in Germany but did affect N offtake significantly in France and Denmark (Table S4). In 2022, fertilization had a significant effect on N offtake at all sites (Table S4).

In the combined analysis of all trials, fertilization was close to being a significant factor (p=0.0509) for yield (means are shown in (Table S7)). The factors of trial site, year, and interaction of trial site and treatment were not significant. In the analysis of crop N offtake, the fertilization treatment was significant in the combined analysis of all trials. Here, the two highest mineral references differed significantly from the lowest (0), but not from the majority of the BBFs, which also did not differ significantly from each other (Table S7).

Table 4

ANOVA of first-year fertilization treatments (Table 2) followed by Fisher's LSD test separately for each site and each year (2021 and 2022). LSD means of grain yields estimated from the model (kg ha^{-1}) (grain maize, spring barley, winter wheat, and spring wheat), whole-crop yield (silage maize), and p-values of tests. Means followed by a common letter are not significantly different in the LSD test at the 5 % level of significance. Local BBFs are displayed in italics. "SE" is the modeled pooled standard error for all treatments. "REF_1-5" are mineral references with ascending N application.

	France (p-value: <0.0001)			**Germany** (p-value: <0.0001)			**Denmark** (p-value: 0.0002)		
		Yield⁋	LSD		Yield⁋	LSD		Yield†	LSD
Fertilization in 2021	SE	916		SE	1078		SE	747	
	BA6	15152	a b	BA6	15964	b c d e	BA6	5651	a b c
	BIO	15835	a b	BIO	18153	a b c	BIO	4327	a b c d
	ECO	16010	a b	ECO	15372	d e	ECO	6446	a
	FEK	16093	a b	FEK	16765	c d e	FEK	6174	a
	MO13	13620	a	MO13	16528	c d e	MO13	5375	a b c d
	OG2	15847	a b	OG2	18081	a b c	OG2	5854	a b
	PAL	16211	a b	PAL	18329	a b c	PAL	.	
	FR13	17092	a	*ASL1*	17748	a b c d	*BVC*	3694	c d
	FR8	15992	a b	*ASL2*	18319	a b c	*PCW*	5487	a b c
				GRF	.		*SDG*	5792	a b c
				MAL	16716				
	Ref_1	8400	d	Ref_1	14484	e	Ref_1	3257	d
	Ref_2	.		Ref_2	17083	a b c d e	Ref_2	.	
	Ref_3	14047	b c	Ref_3	17436	a b c d	Ref_3	3793	b c d
	Ref_4	16571	a b c	Ref_4	19528	a	Ref_4	5216	a b c d
	Ref_5	15016	a b	Ref_5	19098	a b c	Ref_5	6449	a

	France (p-value: <0.0001)			**Germany** (p-value: 0.0303)			**Denmark** (p-value: <0.0001)			**Finland** (p-value: <0.0001)		
		Yield†	LSD		Yield†	LSD		Yield†	LSD		Yield†	LSD
Fertilization in 2022	SE	263		SE	378		SE	662		SE	143	
	BA6	5620	a b c d	BA6	5378	e f	BA6	3957	b c d	BA6	3500	d e
	BIO	5755	a b	BIO	6551	c d	BIO	3123	d e	BIO	3690	b c d
	ECO	5672	a b c	ECO	5692	d e	ECO	3884	b c d e	ECO	3888	b c
	FEK	5485	a b c d	FEK	6012	d e	FEK	5538	a b	FEK	3697	b c d
	MO13	5033	a b c d	MO13	6013	d e	MO13	4154	b c d	MO13	3781	b c d
	OG2	5103	b c d	OG2	5254	e f	OG2	3385	c d e	OG2	2958	f
	PAL	5648	a b c	PAL	6492	c d	PAL	5374	a b	PAL	4006	a b
	FR13	*5355*	c d	*ASL1*	*6145*	d e f	*BVC*	*2487*	d e	*AV8*	*3113*	f
	FR8	*4924*	d	*ASL2*	*6665*	c d	*PCW*	*6144*	a	*BO4*	*3688*	b c d
				GRF	*4984*	e	*SDG*	*5625*	a b	*FEL*	*3648*	c d
				MAL	*5629*	d e						
	Ref_1	2776	e	Ref_1	3107	g	Ref_1	2047	e	Ref_1	2191	g
	Ref_2	.		Ref_2	5233	e f	Ref_2	.		Ref_2	3197	e f
	Ref_3	5453	a b c d	Ref_3	7350	b c	Ref_3	5037	a b c	Ref_3	3759	b c d
	Ref_4	5815	a	Ref_4	8317	a b	Ref_4	5030	a b c	Ref_4	3942	a b c
	Ref_5	5551	a b c d	Ref_5	8706	a	Ref_5	6305	a	Ref_5	4247	a

⁋ Yield displayed as dry matter, † Yield displayed at 15 % moisture content.

At the French site, all BBFs had yields similar to that of the highest mineral reference in both 2021 and 2022 (Table 4 and Fig. 2). At the German site, all BBFs except ECO had yields similar to the two highest references in 2021. However, the yields for BA6, ECO, FEK, and MO13 did not differ significantly from the unfertilized reference, which had a relatively high yield and hence a relative small response to increasing mineral N input (Fig. S1). In 2022, all BBFs had significantly lower yields compared to the two highest references at this site, but significantly higher yields than the unfertilized reference. At the Danish site, all of the BBFs except BVC resulted in yields similar to the highest reference in 2021. In 2022 however, all BBFs except FEK, PAL, PCW, and SDG had significantly lower yields than the highest reference. By contrast, compared with the second-highest reference, only BIO and BVC had significantly lower yields, all others had yields similar to the second-highest reference. At the Finnish site, only BA6, OG2, and AV8 had a significantly lower yield compared to the second-highest reference in 2022. However, only PAL had a similar yield to the highest reference. All BBFs had a significantly higher yield than the unfertilized reference. Data for the yield of the mineral fertilizer references for both years and all sites can be found in the supplementary material (Fig. S1).

3.1.2. *Residual fertilizer effect of BBFs in the second year*

The evaluation of the residual fertilizer effect in 2022 showed the lowest yields for the unfertilized 2021 reference (Ref_1) at all sites (Table 5) and a clear residual fertilizer response for the trial sites France, Germany, and Denmark of the gradually increasing fertilizer levels of the other references (Fig S1-C). Although the residual effect is clearly evident in the mineral references (Fig. S1), the 2021 fertilization (mineral references and BBFs) had no statistically significant effect on 2022 yields obtained at the sites in France, Denmark, or Finland (Fig. 3, Table 5), i.e. the residual effects of mineral fertilizer and BBFs are not significantly different when applied at the same N level. However, in Germany, the residual effect of fertilization in 2021 had a significant effect on the winter wheat yield in 2022 (Table 5). Here, OG2 and both the highest and second-highest mineral references obtained significantly higher yields than the unfertilized reference. Yet no BBFs had higher residual fertilizer effects than the mineral reference applied at the same N level. Additionally, the 2022 fertilization had a significant effect on spring barley yield in 2023 at the German site (Table S5). However, none of the treatments in Germany differed from the unfertilized reference in 2023. When comparing the trial sites, there was a tendency for the BBFs to have higher yields than the corresponding mineral reference in the second year at the French and Danish sites (Fig. 3). However, in Germany, the residual fertilizer effect was lower than that of the corresponding mineral reference.

The fertilization in 2021 had no significant effect on residual N offtake in 2022 at any of the sites (Table S6). A comparison of the sites shows that the BBFs in France resulted in comparable high N offtake as the mineral references. In Germany, the N offtake was lower for BBFs than for the corresponding mineral reference.

3.2. *Nitrogen fertilizer replacement values*

In the year of application, the $NFRV_{AE}$ varied greatly from 11 % (BVC 2022 Denmark) to 113 % (FR13 2021 France) (Fig. 4). The average NFRV across sites and years for all BBFs was higher when based on agronomic efficiency, $NFRV_{AE}$ (70 %) compared to when estimated from N use efficiency, $NFRV_{NUE}$ (58 %) (data shown in Fig. S4). Across sites and years and for all BBFs, the average $NFRV_{AE}$ was higher (76 %) when BBFs were incorporated than when surface applied (64 %).

Together, the seven common BBFs and the eleven local BBFs tested individually at each site, 18 BBFs were tested in this study (19 different treatments, since ASL was applied in two different ways). Of these, eight had high agronomic performances with an $NFRV_{AE}$ above 75 % (ranking FR13>PCW>BO4>FEL>PAL>SDG>>FR8>FEK), seven had an intermediate $NFRV_{AE}$ of 60–75 % (ranking ASL2->ECO>BIO>MO13>BA6>OG2>ASL1) and four had a low $NFRV_{AE}$ of 10–60 % (ranking AV8>MAL>GRF>BVC).

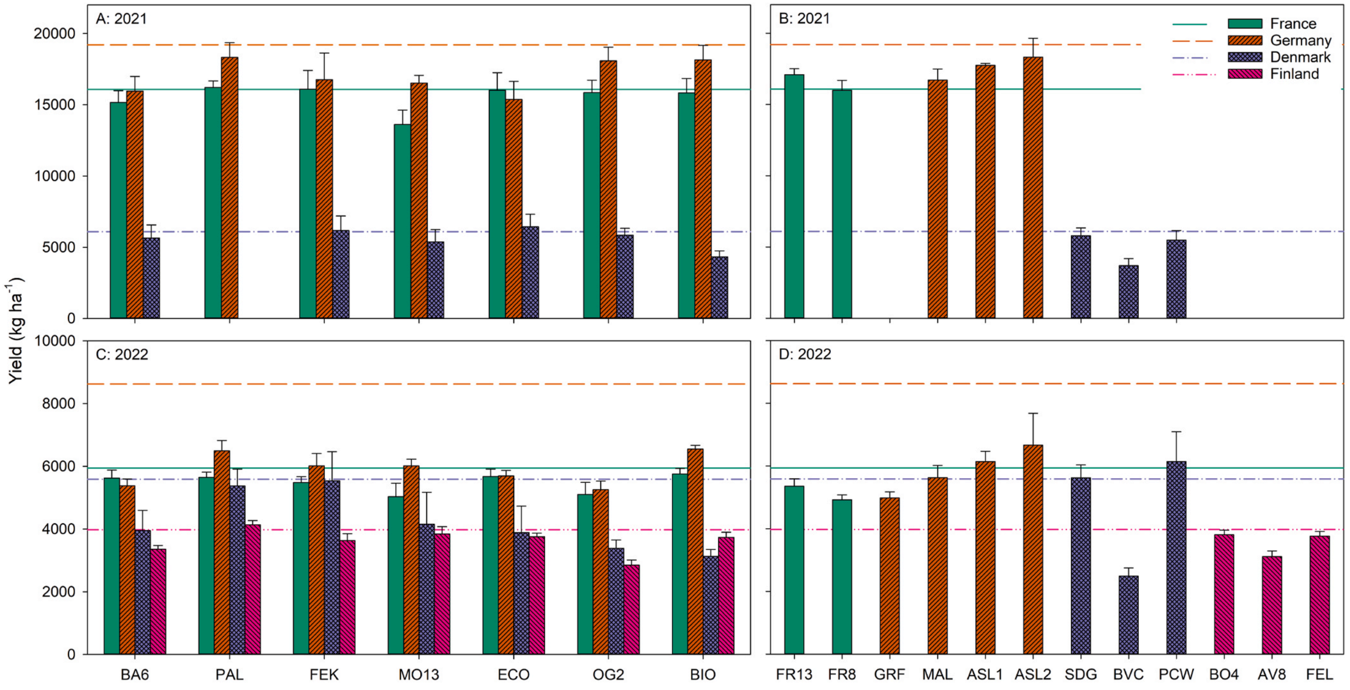

Fig. 2. Means ± standard error of recorded yield (kg ha^{-1}) of silage maize (Germany 2021) and grain yield (kg ha^{-1}) of grain maize (France 2021), spring barley (Denmark 2021), winter wheat (France, Germany and Denmark 2022) and spring wheat (Finland 2022). Values are given for dry matter for silage maize and grain maize and at 15 % moisture content for all cereal grains. The yields obtained with the seven common BBFs (Table 2) tested at all sites are shown as bars in A (2021) and C (2022). Yields from the local BBFs are shown in B (2021) and D (2022). The horizontal lines indicate the site-specific mean yield of the mineral N reference fertilizers at the same application rate as the BBFs. Application rates differed between sites and years. $n = 4$. Note different scale on the vertical axis for the two years.

Table 5

ANOVA of residual second-year fertilization treatments (Table 2) using Fisher's LSD test separately for each site in 2022 (fertilization in 2021) in winter wheat. LSD means (kg ha^{-1}) of grain yields estimated from the model at 15 % moisture content and p-values of tests. Means followed by a common letter are not significantly different in the LSD test at the 5 % level of significance. Local BBFs are displayed in italics. "SE" is the modelled pooled standard error for all treatments. "REF_1-5" are mineral references with ascending N application.

France (p-value: 0.41)			**Germany** (p-value: <0.02)								**Denmark** (p-value: 0.41)			**Finland** (p-value: 0.19)		
	Yield	LSD		Yield	LSD							Yield	LSD		Yield	LSD
SE	605		SE	342							SE	269		SE	264	
BA6	3450	-	BA6	3081					e	f	BA6	2404	-	BA6	4282	-
BIO	3188	-	BIO	3263		b	c	d	e	f	BIO	2348	-	BIO	4234	-
ECO	3499	-	ECO	3445		b	c	d	e	f	ECO	2523	-	ECO	4482	-
FEK	2976	-	FEK	3472	a	b	c	d	e	f	FEK	2329	-	FEK	3629	-
MO13	4031	-	MO13	3372		b	c	d	e	f	MO13	2677	-	MO13	4085	-
OG2	3008	-	OG2	3730	a	b					OG2	2542	-	OG2	4215	-
PAL	3832	-	PAL	3256		b	c	d	e	f	PAL	.	-	PAL	3546	-
FR13	3288	-	*ASL1*	3607	a	b	c	d			*BVC*	1998	-	AV8	4143	-
FR8	3458	-	*ASL2*	3671	a	b	c				*PCW*	2594	-	BO4	3489	-
			GRF	.							*SDG*	2078	-	FEL	3819	-
			MAL	3508	a	b	c	d	e							
Ref_1	2518	-	Ref_1	2979						f	Ref_1	1794	-	Ref_1	3832	-
Ref_2	.	-	Ref_2	3151				d	e	f	Ref_2	.	-	Ref_2	4018	-
Ref_3	2999	-	Ref_3	3183			c	d	e	f	Ref_3	2032	-	Ref_3	4132	-
Ref_4	3024	-	Ref_4	3556		b	c	d	e		Ref_4	2082	-	Ref_4	4211	-
Ref_5	3393	-	Ref_5	3980	a						Ref_5	2481	-	Ref_5	3845	-

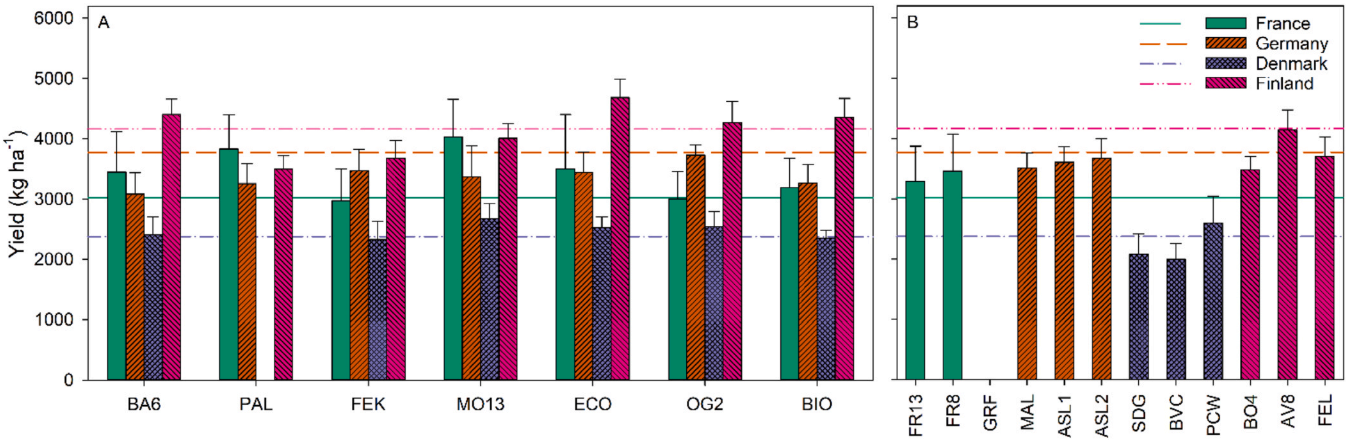

Fig. 3. Means ± standard error of recorded yield (kg ha^{-1}) (residuals of 2021) at 15 % moisture content for winter wheat (France, Germany and Denmark) and spring wheat (Finland) in 2022. The yields obtained with the seven common BBFs (Table 2) tested at all sites are shown as bars in A. The local BBFs are shown as bars in B. The horizontal lines indicate the mean yield of the mineral N reference fertilizers at the same application rate (2021) as the BBFs. The yields were obtained in 2022 from the plots fertilized in 2021 to measure the second-year residual fertilizer value. Application rates differed between sites. $n = 4$.

In general, the BBFs had a positive residual NFRV$_{\mathrm{AE}}$ in the second year after application (Fig. 5). In France and Denmark, the residual NFRV$_{\mathrm{AE}}$ of the BBFs was mainly higher than the mineral N reference applied at the same total N rate, and in the range 17–40 %. At the German site however, the values of the residual NFRV$_{\mathrm{AE}}$ of the BBFs were all below that of the mineral N reference applied at the same total N rate. In Finland, some of the BBFs have higher, some have lower residual value than the mineral references, two even negative values (but not significantly different from nil).

4. Discussion

4.1. First-year agronomic performance of BBFs in 2021 and 2022

The BBFs generally resulted in high and comparable yields relative to mineral references at most sites, but also somewhat lower relative yields compared with mineral references in Germany (Fig. 2), where the yield level was very high even at none or low mineral N application (Fig. S1), due to generally high soil fertility of the German site. The combined data analysis of all trials showed that the BBFs did not differ significantly from each other with regard to yield or N offtake (Table S7). A closer look at the trial sites reveals that nearly all the common BBFs had high yields comparable to the mineral reference applied at the same total N level for the French, Danish, and Finnish sites in both years (Table 4). During the two-year multisite trial, we observed no consistency in the ranking of individual fertilizers over the years or between sites. It is important to note that the factors "site" and the interaction of "site" and "fertilization treatment" were not significant, and that "site" is partly confounded with the application methods in this study. However out of the 18 BBFs tested, eight had high average agronomic performance with NFRV$_{\mathrm{AE}}$ above 75 %, while six had an intermediate NFRV$_{\mathrm{AE}}$ of 60–75 %. For the ASL, direct injection (ASL2 treatment; Table 2) increased the NFRV$_{\mathrm{AE}}$ from the intermediate to high range. In summary, this suggests that the majority of the BBFs can act as reasonably effective substitutes for mineral N fertilizers (hypothesis I confirmed). However, their fertilization effect varies between agricultural settings of the trial sites, but not in a consistent way (see Section 4.3).

Zandvakili et al. (2019) stated that the C/N ratio of organic fertilizers determines the release of plant-available N and that BBFs with C/N ratios above 7–8 release far less plant-available N. This contrasts with the

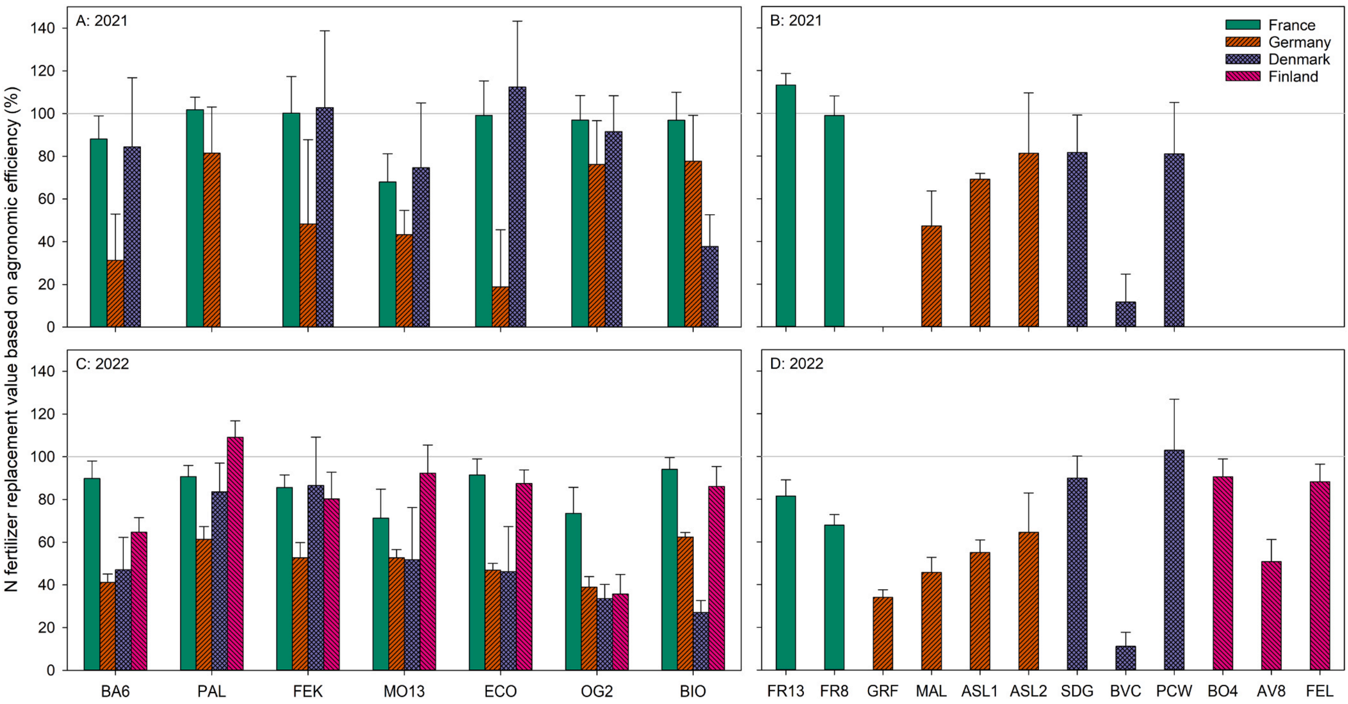

Fig. 4. Means ± standard error of $NFRV_{AE}$ (%) in the year of application. The seven common BBFs (Table 2) tested at all sites are shown as bars in A (2021) and C (2022). The local BBFs are shown in B (2021) and D (2022). The horizontal grey line indicates 100 % $NFRV_{AE}$, i.e. where the BBF performs equally well as the mineral N reference at the same application rate. Crops and application rates differed between sites and years. $n = 4$.

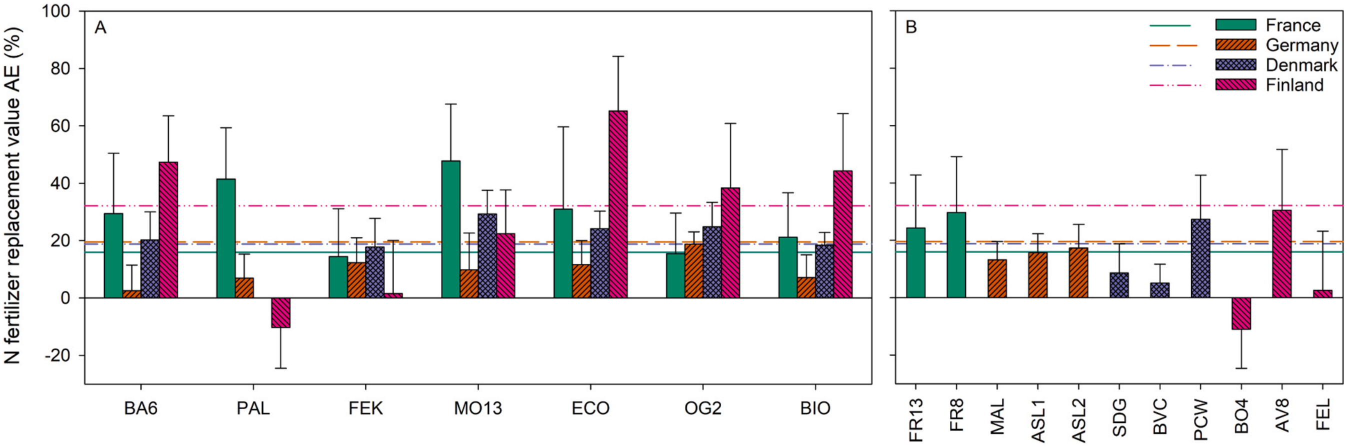

Fig. 5. Means ± standard error of residual (second year) $NFRV_{AE}$ (%) in the year following BBF application. The seven common BBFs (Table 2) tested at all sites are shown in A, the local BBFs in B. The horizontal lines indicate the mean residual (second-year) $NFRV_{AE}$ (%) of the mineral N reference fertilizers at the same application rate (2021) as the BBFs. The crop is winter wheat (France, Germany and Denmark) and spring wheat (Finland) in 2022. Application rates differed between sites. $n = 4$.

findings in the current study where no relation between C/N ratio of the BBFs (Table 2) and the agronomic performance of BBFs was found. As an example, FEK with a C/N ratio of almost 9 had a high average $NFRV_{AE}$ of 79 %. Additionally, the agronomic performance of the BBFs did not correlate with any of the other assessed properties of the BBFs (pH, total N, NH_4^+, NO_3^-, DM, total C content) (data not shown). Even though BBFs with a high total N content did not have a higher agronomic performance than those with low total N content, a high BBF total N content is an advantage for transport, storage and application, as smaller fertilizer quantities need to be handled and field applied. Furthermore, BBFs with a high mineral N content (NH_4^+-N and NO_3^--N) did not perform better than those with a low mineral N content. Thus, the data in this study suggest that BBFs should be applied based on their total N content and not mineral N content (NH_4^+-N and NO_3^--N), as is common for more traditional organic fertilizers like animal manures and slurries.

The compost (BVC, one of the local, Table 2) was the only BBF that did not consistently differ from the unfertilized reference and therefore had no significant fertilizer effect (Table 4). Composts have also in previous studies been found to give lower yields compared to mineral N fertilizers based on total N addition (Chalk et al., 2013; Gutser et al., 2005; Ronga et al., 2019). Based on the definition in Wester-Larsen et al. (2022), BVC can thus not be defined as a BBF, since it does not produce a fertilizing effect; rather it should be considered a soil amendment or amelioration product.

Apart from the low agronomic performance of the compost, no general statement on agronomic performance can be made based on the

BBF source materials and production technologies. The two digestates (both tested locally, Table 2) included in this study performed very differently, with higher yield responses for SDG (Danish site) compared to GRF (German site). This may be due to differences between the two sites and weather conditions on the day of application (precipitation in Denmark, sunshine in Germany). But the two digestates also differed in origin and compositions as GRF is the liquid fraction of mechanically separated digestate from an anaerobic digestion (AD) plant using manure and crop feedstocks, whereas SDG consists of unprocessed whole digestate from an AD plant using seaweed, agro and food waste as feedstocks. However, previous studies have reported agronomic performances equal to mineral references both for digestates and liquid-fraction digestates (Cavalli et al., 2016; Luo et al., 2022), as was found for SDG at the Danish site.

4.2. Second-year residual fertilizer effect of BBFs

Although there is no significant difference in residual fertilizer effects of BBF and mineral reference in the second year after application in France, Denmark, and Finland, the strong responses of the increasing levels of mineral N references at all sites indicates that fertilization had a marked residual effect on the following crop in this study. The large modelled standard errors for the residual effect data for France, Denmark and Finland (Table 5) are mainly due to a high variance of the BBF data from the experimental fields. Even in Germany where the residual fertilizer effect was significant in 2022 and 2023, the differences between the BBFs were not useful for interpretations (Table 5, Table S5; Fig. 3). The lack of a significantly higher residual fertilization effect of the BBFs compared to the mineral N reference can possibly be attributed to the relatively high average first-year fertilization effect, with the first-year crop utilizing the largest proportion of the N in the BBF, and residual mineralization of remaining BBF organic N being correspondingly low. Based on this BBFs that did not have a high agronomic performance in the first year could be expected to have a higher residual effect. However, this was not found to be the case in this study (Fig. 2 vs. Fig. 3), but we can only speculate if it is due to lack of synchrony of the residual N availability from these BBF and subsequent crop demand, leading to N losses. When comparing the relatively low yields (Fig. 3) and N offtake (Fig. S3) per site, it can be noted that most BBFs achieved higher yields and N offtake compared to the mineral reference at the same total N level, even though at the German site they all were lower. Therefore, we conclude that even if BBFs have a second-year fertilizing effect which tends to be higher than that of mineral fertilizers, this was not found to be significant in this study (hypothesis II rejected).

Zavattaro et al., (2015) performed a meta-analysis on European long-term trials and found that the effect of organic fertilizers (manure, slurry and compost) improved with the duration of repeated application. Schröder (2005) carried out a model simulation of N mineralization with repeated annual applications of manure and found that the N mineralization increases due to previous applications. Moreover, after several years of repeated manure application an equilibrium is reached between the amount of N applied annually and the amount of N mineralized annually. In the current study, the residual fertilization effect of a single application only was studied. Thus, if the trial had been continued for more years and had been designed with continuous application of the BBFs, a residual fertilization effect from previous years may have been detected as significant.

4.3. Implications of agricultural and geographic setting

At the German high soil fertility trial site, the seven common BBFs generally resulted in lower yield response than the corresponding mineral reference. This stands in contrast to the findings at the other sites with overall comparable yield responses to the corresponding mineral reference. Based on a meta-study of European long-term trials with compost, manure and slurry, Zavattaro et al. (2015) found that organic fertilizers result in higher yields in cooler climates and on coarse-textured soils. With a texture of 30 % clay, 68 % silt and only 2 % sand (Table 1) the German soil had the finest texture of the four sites. Together with the high background fertility (low N responsiveness) of the soil, this could possibly explain the lower yield responses to the BBFs. However, BBFs do not generally appear to result in higher yields in cooler climates in this study. This could be due to drier summers compared to the climate norm in 2021 and 2022 at the Danish and Finnish sites (Fig. 1). Despite variation in agronomic efficiency between years and sites, soil type and climate could not be identified as significant factors for the agronomic efficiency of the BBFs across sites (hypothesis III partly rejected). One reason for this could be that the different N species/sources of the BBF (Table 2) had a greater influence than soil type and climate, as it can be assumed that soil moisture and temperature influenced the N availability differently depending on whether the source of N of the BBFs is of a more recalcitrant or easily mineralizable organic form (Agehara and Warncke, 2005) or even mainly inorganic. The N species/sources in this study ranged from mineral N (ASL) to complex organic N species like keratins (OG2, MO13). Since this study was designed to test for the agronomic performance of BBFs across Europe, our design did not allow us to test different BBF mineralization patterns across different soils and sites.

Compared to the mineral reference at the same N application rate, the BBFs resulted in higher yields for the spring crops (2021 all sites, 2022 Finnish site) with immediate BBF soil incorporation than the winter crops with BBF surface application (2022 French, German and Danish sites). Overall, the BBFs had a $NFRV_{AE}$ which was on average 16 % higher when incorporated than when surface applied. When incorporated, the BBFs are less prone to environmental influences, and it may reduce the risk of ammonia volatilization (Müller et al., 2023; Wester-Larsen et al., 2023). However, it should be remembered that the effect of application was partly confounded with site in this study.

The three local liquid BBFs applied both years (SDG, PCW and ASL; Table 2) differed less in $NFRV_{AE}$ between the two years compared to the solid BBFs. As suggested by Ehmann et al. (2018) and (Luo et al., 2022), it could be speculated that the liquid BBFs would not be affected by the application method to the same extent as the solid BBFs, as they are better able to infiltrate the soil. However, the digestate SDG has previously been shown to have a high potential NH_3 volatilization compared to the other BBFs (Wester-Larsen et al., 2022). Thus, the slightly lower $NFRV_{AE}$ of 77 % for SDG in 2022 when surface applied compared to 82 % in 2021 when incorporated may be due to NH_3 volatilization. Solid BBFs applied on the soil surface rely on precipitation for their disintegration, dissolution and infiltration into the soil root zone. The physical properties of the BBFs were not thoroughly assessed in this study, but a visual assessment of the surface applied solid BBFs at the Danish and German trial in 2022 found that they were all still visible on the soil surface two weeks after application (Fig. S6 in supplementary material). Moreover, the BBFs can be more prone to being eaten by wild animals when they are surface applied compared to incorporation (Fig. S5). While the primary focus of the current study was on the NFRV of the BBFs, it is crucial to bear in mind that they also contain other nutrients, like P and K, essential for plant growth (Chojnacka et al., 2020; Prado et al., 2022). Applying BBFs as a sole N fertilizer would for many of the BBFs result in an imbalanced application of P and K, as indicated by the N:P and N:K ratios in Table 2. For instance, the average N application of 148 kg N/ha (across all sites and years; Table 3) would imply as much as +600 kg K/ha for PCW or as much as +190 kg P/ha for FR8. Both BBFs are extreme examples for K and P, while the majority of the N-rich BBFs used in this trial had low K and P contents. Furthermore, at each of the trial sites, care was taken to ensure that P and K did not become a limiting factor of plant growth by applying recommended rates of mineral P and K for all treatments. But for a more balanced fertilization, relative to crop demand in practical agriculture, some of the BBFs application rate needs to be lowered and supplemented with either mineral N (and P or K) or combined with a suitable complementary BBF, optimizing the N:P:K ratio. Alternatively, the P and K supply of the crops can also be ensured over the entire crop rotation, so the P and K demand of individual crops may be supplied from a BBF application in an earlier season.

5. Conclusions

This two-year study tested seven BBFs on all trial sites and 11 local BBFs, which made up a total of 18 BBFs. It was found that they had a high average mineral N fertilizer replacement value ($NFRV_{AE}$) of 70 % across all sites and years. The $NFRV_{AE}$ varied greatly between BBFs, ranging from 41 % to 113 % (excluding BVC 11 %). Eight of the BBFs had a $NFRV_{AE}$ above 75 %, while six fell within the range of 60–75 %. This indicates that most of the BBFs can be regarded as reasonably effective substitutes for mineral N fertilizers, as they performed more or less equally well as the mineral reference applied at the same total N level. Although there was variation in agronomic efficiency between years and sites, soil type and climate were not found to be significant explanatory factors for BBF yield effects or $NFRV_{AE}$ across sites.

The application of BBFs resulted in a positive residual fertilizing effect in the second year, which tended to be higher than that of mineral fertilizer references. However, almost no BBF residual N effect were found significantly higher than those of the mineral fertilizers in this study.

The BBFs tended to have a higher agronomic performance when incorporated into the soil, compared to soil surface application. This suggests that BBFs are better suited for spring crops, as it is usually not technically feasible to incorporate solid fertilizers in growing crops. However, field trials designed specifically to test the application method are necessary to confirm this.

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CRediT authorship contribution statement

Salo Tapio: Methodology, Investigation, Conceptualization. **Lærke Wester-Larsen:** Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Lars Stoumann Jensen:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Benedikt Müller:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Torsten Müller:** Writing – review & editing. **Andrea Bauerle:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Aurélien D′Oria:** Writing – review & editing. **Iris Lewandowski:** Writing – review & editing. **Ramiro Recena Garrido:** Investigation. **Mustapha Arkoun:** Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lars Stoumann Jensen reports financial support was provided by European Commission.

Data availability

All data is openly available online in ERDA, the repository of the University of Copenhagen: https://doi.org/10.17894/ucph.ae55cc62-1993-418c-aeb1-e7c6ee808bb3

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2024.109486.

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