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PAPER

Bio-based fertilizers can reach agronomic performance of synthetic fertilizer in broccoli production under two climate scenarios

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Abstract

Bio-based fertilizers (BBFs) are part of the circular economy model for Europe to achieve climate neutrality by 2050, decoupling economic growth from resource exhaustion and maintain agronomic production within planetary boundaries. Here, an Ecotron experiment evaluated agronomic performance and greenhouse gas (GHG) emissions (N_2O, CO_2) of four BBFs compared to a synthetic fertilizer (SYN) in broccoli production under a historic reference and a future RCP8.5 climate scenario for Belgium. Crop production parameters such as element use efficiencies and yield were similar or lower for plants receiving BBFs compared to SYN in the reference climate, but similar or higher for BBFs compared to SYN in the future climate. Mechanistically, cropping systems with BBFs benefited from enhanced soil microbial activity compared to SYN in both climates (measured as hydrolysis of fluorescein diacetate), but concurrently also had higher GHG emissions. The risk of nitrate leaching was indifferent amongst fertilizers but globally increased in the future climate with more intense dry-rain shifts. While these results support BBFs as agronomic alternatives to SYN, further research is needed to address climate-induced yield penalties which were observed for all fertilizers (BBFs & SYN) in the future climate.

1. Introduction

Implementing sustainable, reliable and profitable land management practices which also work under the more challenging environmental conditions anticipated for the future is key for food security and to meet the targets of the Paris Agreement (EEA 2019). Agriculture is not only essential to feed a growing world population but is also at the heart of the triple planetary crisis of climate change, pollution and biodiversity loss (IPCC 2021, Richardson *et al* 2023). Therefore, it is essential to identify land management practices which increase resource use efficiency while reducing greenhouse gas (GHG) emissions.

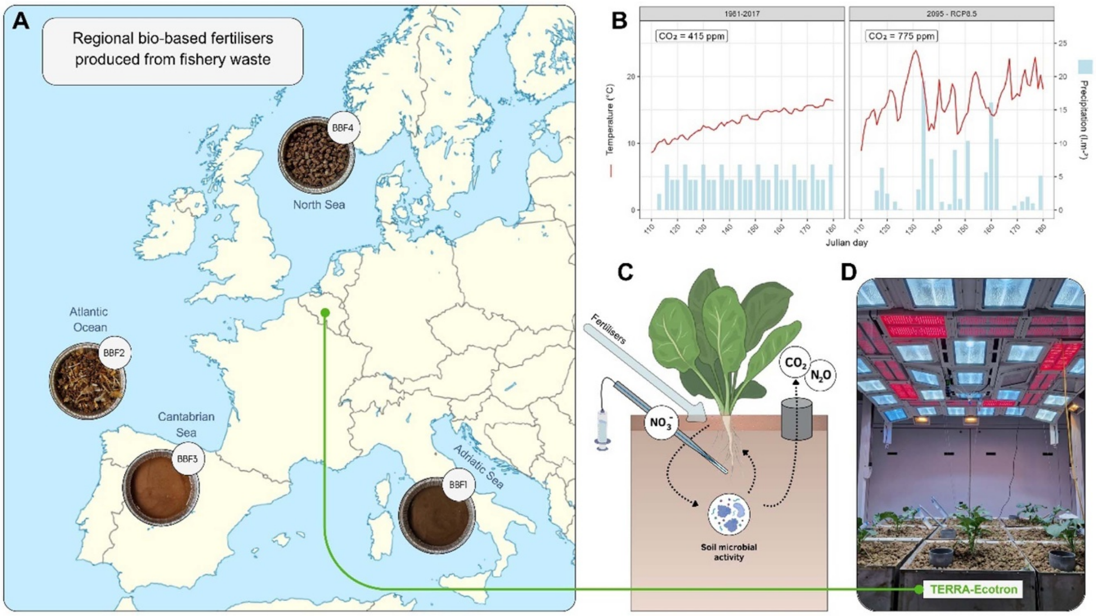

Figure 1. Experimental set-up. Agronomic and environmental performance of four bio-based fertilizers (BBFs) from the main European fishery areas (A) were evaluated against a synthetic fertilizer (SYN). Crops were grown in two climate scenarios (B): the smoothened mean of historical climate data (1981–2017) from the Ernage weather station (50°33′54.8104″N, 4°42′9.9349″E) providing a favorable range of meteorological conditions for plant growth and fertilizer uptake, and a regional future climate scenario according to the RCP8.5 for the year 2095. The tested crop was broccoli (*Brassica oleracea* var. *italica* cv. *Koros*) grown in intact soil monoliths (125 000 cm^3 each) excavated in an arable field in vicinity to the weather station prior to the experiment (C), (D).

The introduction of synthetic fertilizers revolutionized agricultural production, but overuse of fertilizers causes environmental degradation such as soil acidification, which in turn is detrimental to agricultural production (Erisman *et al* 2008, Tian and Niu 2015). Many regions do not produce their own fertilizer and hence rely on fertilizer imports, making them vulnerable to geopolitical instability and market shifts (World Bank Group 2021, Glauben *et al* 2022, Quitzow *et al* 2025). Recycling organic materials and waste from local industries to create nutrient-rich fertilizers for crops offers a promising solution for economic independence, while also reducing waste and optimizing the use of planetary resources (Ellen MacArthur Foundation 2015, Chojnacka *et al* 2020, Priya *et al* 2023). Agricultural commodities are an essential part of global trade, with the European Union being a major importer and exporter of agri-food products globally, and one of the largest seafood markets (FAO 2024, EC 2024a). The sea food and fisheries sector produce a significant amount of nutrient-dense organic waste, which can represent between 30 and 70% of overall catch (Toppe *et al* 2018). Valorizing these waste products by transforming them into bio-based fertilizers (BBFs) is part of the circular economy model which reduces waste and increases resource efficiency. While BBFs can have varying levels of primary macronutrients such as nitrogen (N), phosphorous (P) and potassium (K), recent advances in technologies like amino acid recovery, fish emulsions, and pelleting have significantly improved their quality and stability (Toppe *et al* 2018, Zhang *et al* 2023). With proper processing and monitoring, recycling organic materials into BBFs can therefore be a sustainable alternative to synthetic fertilizers. However, the suitability of BBFs for large-scale field applications remains poorly tested and data on the competitive performance of BBFs compared to synthetic fertilizers is equally scarce. In this context, to establish the market potential of BBFs for the future, it is key to assess fertilizer performance under realistic future meteorological conditions taking multiple climate change components into account, such as elevated CO_2, temperature, irradiation and altered rainfall patterns. To this end, this study evaluated how four different BBFs derived from fishery by-products of the main European fishing sectors perform in comparison with a synthetic fertilizer under a reference and a projected future climate scenario (figure 1). Specifically, the study determined whether the selected BBFs could sustain crop productivity in direct comparison to a synthetic fertilizer, evaluated nutrient-use efficiency for nitrogen and phosphorous, and the environmental impact in terms of edaphic N_2O and CO_2 emissions, as well as the risk of nitrate leaching. This experiment thus provides new insights to the behavior of cropping systems using BBFs from fishery waste and assesses their agronomic and environmental robustness under climate change.

2. Material and methods

2.1. Climate scenarios

The meteorological conditions were applied in the TERRA-Ecotron, which allows to realistically simulate virtually any meteorological condition through high-resolution control of temperature, humidity, precipitation, irradiation, air flow and GHG concentrations (Roy *et al* 2021). For this experiment, two climate scenarios were applied: (i) a control climate aiming to provide a favorable environment for crop growth and fertilizer uptake, and (ii) a future projection of meteorological conditions to test the agronomic and environmental performance of the fertilizers in the future. The control climate was the smoothened mean of historical climate data from 1981 to 2017 recorded at the Ernage weather station, Belgium (50°35′30.6″N 4°40′19.9″E). The historic data was then used to predict future meteorological conditions for the period of 2070–2100 using the Alaro-0 model (Giot *et al* 2016) and based on the Representative Concentration Pathway 8.5 W m^{-2} scenario (IPCC 2021). The experiment then ran in the spring and early summer (April–June) of the historic reference climate and the projected year 2095 simultaneously in replicated experimental units. The future climate in comparison to the reference climate was characterized by higher atmospheric CO_2 concentrations (775 ppm vs 415 ppm) and higher temperature (mean 15.4 °C vs 12.9 °C), at similar rain quantities (mean 2.2 mm d^{-1}), but which in 2095 were distributed in more intense rain/drought events (figure 1(B)).

2.2. Experimental set-up, fertilizer application and crop management

Intact and undisturbed soil monoliths with a dimension of 50 × 50 × 50 cm each (125 000 cm^3) were excavated in an arable field (50°33′54.8104″N, 4°42′9.9349″E) in April 2024 and moved to the TERRA-Ecotron. Prior to sampling, the field had a 2 year succession of textile hemp (*Cannabis sativa* subsp. *Sativa*, 2023 and 2022), preceded by two years of a temporary meadow covered with grass (mix of *Lolium perenne, Agrostis stolonifera, Alopecurus pratensis, Phleum pratense, Agrostis capillaris, Ranunculus acris, Trifolium pratense, Lotus corniculatus*, 2021 and 2020), preceded by maize (*Zea mays*, 2019). No plant protection or fertilizer products were used on hemp or grassland, but nitrogen fertilizer was applied for maize cultivation in 2019. At the time of cube excavation, soil samples were taken in the 0–20 cm topsoil in the field to quantify basic soil properties and the present mineral soil nitrogen content to adjust the amount of fertilizers to be applied in each cube accordingly (SM3). Once moved to the controlled environment rooms (CERs) of the TERRA-Ecotron, cubes were manually weeded and left to acclimatize for six days. Thereafter, each cube was planted with one individual broccoli seedling at the two-leaf stage. The here studied cultivar (*Brassica oleracea* var. *italica* cv. *Koros*) was selected as a representative member of the global broccoli population given its accomplished horticultural performance and widespread use within the EU (EC 2023). The experiment was structured in a randomized block design, where each climate was reproduced in three CERs simultaneously ($n = 6$ total). Each of the four BBFs and the synthetic fertilizer (SYN) were replicated in five cubes, which resulted in a total of $n = 25$ cubes per climate spread amongst the three CERs (table 1, SM4). The overall production cycle spanned eight weeks, starting on 21 April (Julian day 111) and concluding on 23 June (Julian day 174) in simulated time. Fertilization was applied in a single dose to the soil surface one day before planting and the soil was manually ploughed in the first 5 cm afterwards. The quantity of fertilizer to be added was calculated for each fertilizer individually based on its nitrogen content to reach a total of 120 kg N ha^{-1} for all treatments, summing respective fertilizer N and the initial soil mineral nitrogen contents. Cubes with broccoli plants were regularly weeded by hand and no plant-protection products were applied.

At the end of the production cycle, broccoli plants were harvested, separated into heads, leaves, stems and crown roots, after which fresh and dry weight were quantified for all compartments. After drying, samples were shredded and then ground.

2.3. Nitrogen and phosphorus contents and element use efficiencies (NUE, PUE)

Carbon and nitrogen contents of the powder from dried plant parts were analyzed via combustion (Vario Max Cube, Elementar, Germany) and phosphorous was analyzed as PO_4^{3-} after removing organic matter at 600 °C and extraction with 19% chloric acid (SmartChem 450, KPM Analytics, UK). The element use efficiencies for nitrogen and phosphorus (NUE, PUE) were subsequently calculated as

$$\mathrm{NUE, PUE} = \frac{\left(N, P_{\mathrm{plantbiomass}} \times \mathrm{dryweight}\right)}{N, P_{\mathrm{fertiliser}} + N, P_{\mathrm{soil}}} \times 100$$

where the amount of the element contained in the above ground biomass (i.e. heads, leaves and stems) was divided by the total amount of respective element provided from fertilizer and soil combined. Initial

Table 1. Characterization of the four bio-based fertilizers (BBFs) and the synthetic fertilizer (SYN) used in this experiment with details on respective marine sourcing region, raw input material, technology, final product classification and chemical composition.

Fertilizer ID	Sourcing region	Raw material	Technology	Fertilizing product	Water content (%)	Organic matter (%)	Nitrogen (N g kg^{-1})	Phosphorous (P g kg^{-1})	Potassium (K g kg^{-1})
BBF1	Adriatic sea	Organic residues from shellfish & fish processing	Enzymatic hydrolysis	Hydrolysates (liquid)	57.88 ± 1.71	82.46 ± 0.21	48.2 ± 1.7	3.25 ± 0.09	14.4 ± 0.26
BBF2	Atlantic ocean	Fish processing waste (head, bone, viscera)	Enzymatic hydrolysis, Thermo-Mechano-Chemical (TMC) fractionation by twin-screw extrusion, drying	Protein fraction (solid)	2.13 ± 0.21	84.45 ± 0.58	80.71 ± 4.3	50.21 ± 6.99	11.08 ± 0.29
BBF3	Cantabrian sea	Fish viscera from fish processing industry	Membrane separation, autolysis	NPK solution w/amino acids (slurry)	49.42 ± 0.27	83.51 ± 0.24	64.07 ± 0.3	28.57 ± 0.88	46.72 ± 2.03
BBF4	North Sea	Dried fish sludge	Drying, palletization	Fish sludge pellet (solid)	17.46 ± 0.42	82.55 ± 0.07	48.50 ± 2.8	32.56 ± 2.26	5.96 ± 0.67
SYN	Synthetic	NO_3, NH_4, Urea, P_2O_5, K_2O, Cu, Fe, Mn, Mo, Zn	Blending, stabilization (EDTA)	Nutrient solution (liquid)	79	—	70	30	50

soil mineral nitrogen was quantified on field samples using a modified Kjeldahl protocol (ISO 11261) and phosphate was quantified as orthophosphate after extraction with 0.5 M $NaHCO_3$.

2.4. CO_2 and N_2O measurements

To measure GHGs, each soil cube was equipped with a PVC tube inserted 7.5 cm into the soil and open at the top and bottom ($h = 15$ cm, $d = 10$ cm). For soil flux measurements, the PVC tubes were closed at the top and connected in a closed-loop system to infrared gas analyzers LI-850 and LI-7820 for measurements of CO_2 and N_2O, respectively (LI-COR Inc., Lincoln, USA). CO_2 and N_2O fluxes were thus measured twice during the first week after fertilization and thereafter weekly throughout the plant production cycle (SM5). For each measurement, the PVC chambers were sealed hermetically and after an initial lag-phase, the gas increase was recorded over a 90 s period. The flux of each gas was calculated as

$$F = \frac{10VP\left(1-\frac{W}{1000}\right)}{RS\left(T+273,15\right)}x\frac{\partial \mathbb{C}'}{\partial t}$$

where F is the soil gas efflux rate (μmol m^{-2} s^{-1}), V is the volume of the chamber above the soil surface (cm^3), P is the pressure in the chamber (kPa), W is the water vapor mole fraction (mmol mol^{-1}), S is soil surface area covered by the PVC chamber (cm^2), T is air temperature (°C), and $\frac{\partial C'}{\partial t}$ $\left(\mu\text{mol}\,\text{mol}^{-1}\right)$ is the rate of change in water-corrected gas mole fraction, calculated by determining the slope of the gas increase in the chamber using linear regression.

2.5. Nitrate in interstitial soil pore water and soil enzymatic activity

Nitrate concentration was measured in interstitial soil pore water extracted from each cube using permanently installed rhizons (Rhizosphere Research Products B.V., Wageningen, The Netherlands). Rhizons are a tubing system which have a porous membrane at one end with a pore size of 0.15 μm, which is inserted into the soil. Applying a negative pressure at the other end of the rhizon allows to suck interstitial soil pore water out of the system, as long as the matric potential is not too low. Here, rhizons with the 9 cm long porous section were placed at the center of each cube at 10–15 cm depth and at a 30–45° angle. Interstitial soil pore water samples were then collected weekly when soil moisture was sufficient and analyzed directly after sampling for the concentration of nitrate (LAQUAtwin NO3-11C, Horiba Ltd, Kyoto, Japan). The average water extractability (%) was calculated for each climate by dividing the number of days with extractable soil pore water by the total number of theoretically scheduled extraction days, multiplied by 100 (SM1-2).

Microbial activity was estimated by measuring enzymatic activity on the basis of the hydrolysis of fluorescein diacetate (FDA) (Adam and Duncan 2001). For each measurement, a composite soil sample was collected combining subsamples of the five replicates of every modality (BBF x climate). Each subsample was 5 g and taken at a depth of 10–15 cm. Microbial activity was measured at four time points (1, 2, 3 and 8 weeks after fertilization). For each measurement, enzymatic activity as quantified as emitted fluorescein using a spectrophotometer (Thermo Scientific Multiskan GO Microplate spectrophotometer, Thermo Fisher Scientific Inc., Waltham, United States) and calculated as

$$\text{FDA activity} = \frac{E_\text{f}xV_\text{b}}{T_\text{r}xP_\text{s}xV_\text{s}}x3600$$

where E_f is the Fluoresceine equivalent in nmol, V_b is the volume of phosphate buffer, T_r is the time in seconds to read a plate, P_s is the dry weight of the soil sample and V_s is the volume of soil in each well.

2.6. Statistical analysis

Differences between climates and comparative behavior of fertilizers were analyzed using Bayesian linear mixed models implemented in R version 4.2.2 with the additional package brms (Bürkner 2017, R Core Team 2024). The first model (1) assessed the response of the whole fertilized system to climate scenario, while the second model (2) was used to evaluate the comparative effect of BBFs to SYN within each climate scenario on the basis of Student's t-distribution. Posterior distributions were subtracted between treatments to compute pairwise comparisons and the probability of direction (pd), ranging from 0.5 to 1, was used to describe effect existence levels (Makowski *et al* 2019). Model outputs were reported with 95% and 75% high density intervals,

$$\mu_{ijk} = \beta_0 + \beta_{\text{climate}[j]} + u_k^{\text{cube}} + \nu_k^{\text{CER}} + \omega_i^{\text{treatment}}, \tag{1}$$

where the modeled mean structure was computed by including one fixed effect (climate), and three random effects (cube, CER and fertilizer treatment) accounting for variability between CERs, experimental units (cube) and fertilization (treatment),

$$\mu_{ijk} = \beta_0 + \beta_{\mathrm{treatment}[i]} + \beta_{\mathrm{climate}[j]} + \beta_{treatment\times climate[i,j]} + u_k^{\mathrm{cube}} + \nu_k^{\mathrm{CER}}, \tag{2}$$

where the modeled mean structure was computed by including two fixed effect (climate and treatment), an interaction factor between these two fixed effects and two random effects (cube and CER) accounting for variability between rooms and experimental units.

To estimate a probability of direction (pd) for plant-available nitrate and soil microbial activity only two random effects (day and treatment) were included in model (1), while in model (2) only one random effect (day) was used. The fixed treatment structure remained unchanged.

3. Results

3.1. Impact of climate on agronomic performance and GHG emissions

Irrespective of the fertilizer used, the future climate mostly had a negative impact on crop growth (figure 2). Especially market-oriented parameters were negatively impacted, with notably reduced broccoli head fresh weight (−122 g, $\mathrm{CI}_{95}[-201.31, -35.84]$, pd = 0.991) and reduced head diameter (−3.01 cm, $\mathrm{CI}_{95}[-4.61, -1.42]$, pd = 0.996) (figures 2(C) and (D)). However, total aboveground plant biomass, comprising heads, leaves, stems, as well as head N and P contents were less and unevenly impacted by climate (figures 2(E) and (F)). Total plant biomass in the future climate increased with BBF1 (+35.67 g dwt, $\mathrm{CI}_{95}[-16.95, +93.44]$, pd = 0.911) and BBF2 (+28.47 g dwt, $\mathrm{CI}_{95}[-33.84, +81.52]$, pd = 0.828), while plants with BBF3, BBF4 and SYN had lower total biomass in the future, with the strongest decrease for SYN (−35.29 g dwt, $\mathrm{CI}_{95}[-93.02, +17.93]$, pd = 0.906).

Phosphorous use efficiency (PUE) overall declined in the 2095 climate scenario (−6.42%, $\mathrm{CI}_{95}[-15.16, 2.55]$, pd = 0.934) (figure 2(B)). The strongest decrease in PUE was observed for SYN (−13.78%, $\mathrm{CI}_{95}[-24.29, -3.34]$, pd = 0.991), while PUE with BBF1 was the least impacted, even displaying a marginal increase (+0.66, $\mathrm{CI}_{95}[-9.42, 11.85]$, pd = 0.536). Nitrogen use efficiency (NUE) was less impacted by climate (pd = 0.577), with minor increases in NUE for BBF1 and BBF2, minor decreases for BBF3 and BBF4, and with SYN showing the strongest decrease (−20.39, $\mathrm{CI}_{95}[-51.21, +6.57]$, pd = 0.922) (figure 2(A)).

On average, N_2O fluxes from the cropping systems declined under the future climate (−2.93 μmol m^{-2}, $\mathrm{CI}_{95}[-6.08, 0.03]$, pd = 0.974) (figure 2(H)). The strongest decrease was observed for systems under BBF4 (−7.95 μmol m^{-2}, $\mathrm{CI}_{95}[-12.91, -2.37]$, pd = 0.999), while N_2O emission for systems under BBF3 and SYN remained mostly unchanged. No consistent climate effect was observed for CO_2 fluxes (figure 2(G)), though systems fertilized with BBF2 showed a slight increase in the future (+3.01 μmol m^{-2}, $\mathrm{CI}_{95}[-0.17, +6.77]$, pd = 0.962).

3.2. Comparing BBFs with SYN

A total of 24 pair-wise comparisons between BBFs and SYN per climate were made for agronomic parameters and a total of eight pair-wise comparisons between BBFs and SYN per climate were made for GHGs (figure 3). In the historic reference climate, those comparison with high probability of direction indicate a better performance of SYN compared to BBF, notably for total plant biomass and element use efficiencies (figures 3(A), (B) and (F)). In the future climate however BBFs became more competitive to SYN with increased agronomic performance and notably improved N_2O-emissions compared to SYN (figure 3(H)). The strongest gain was observed for broccoli head fresh weight of plants fertilized with BBF4 compared to SYN in the future (+103.22 g, $\mathrm{CI}_{95}[-31.35, +221.06]$, pd = 0.951). There was a significant climate × fertilizer interaction, often shifting an inferior performance of BBFs vs SYN in the historic reference climate to a superior performance of BBF compared to SYN in the future climate. For example, total plant biomass produced with BBF1 under the historical climate produced less biomass than SYN under the reference climate (−45.83 g, $\mathrm{CI}_{95}[-78.72, -10.7]$, pd = 0.996), but shifted to a higher biomass production compared to SYN in the future climate (+25.14 g, $\mathrm{CI}_{95}[-3.63, +50.84]$, pd = 0.958) (figure 3(F)). Broccoli head nutrient ($N + P$) content on average decreased in the future climate (−1.58 mg g^{-1} $\mathrm{CI}_{95}[-10.08, 7.83]$, pd = 0.661) but with variable responses amongst the fertilizer × climate modalities, where only for BBF2 head nutrient content was higher than SYN in both climate scenarios (figures 2(E) and 3(E)).

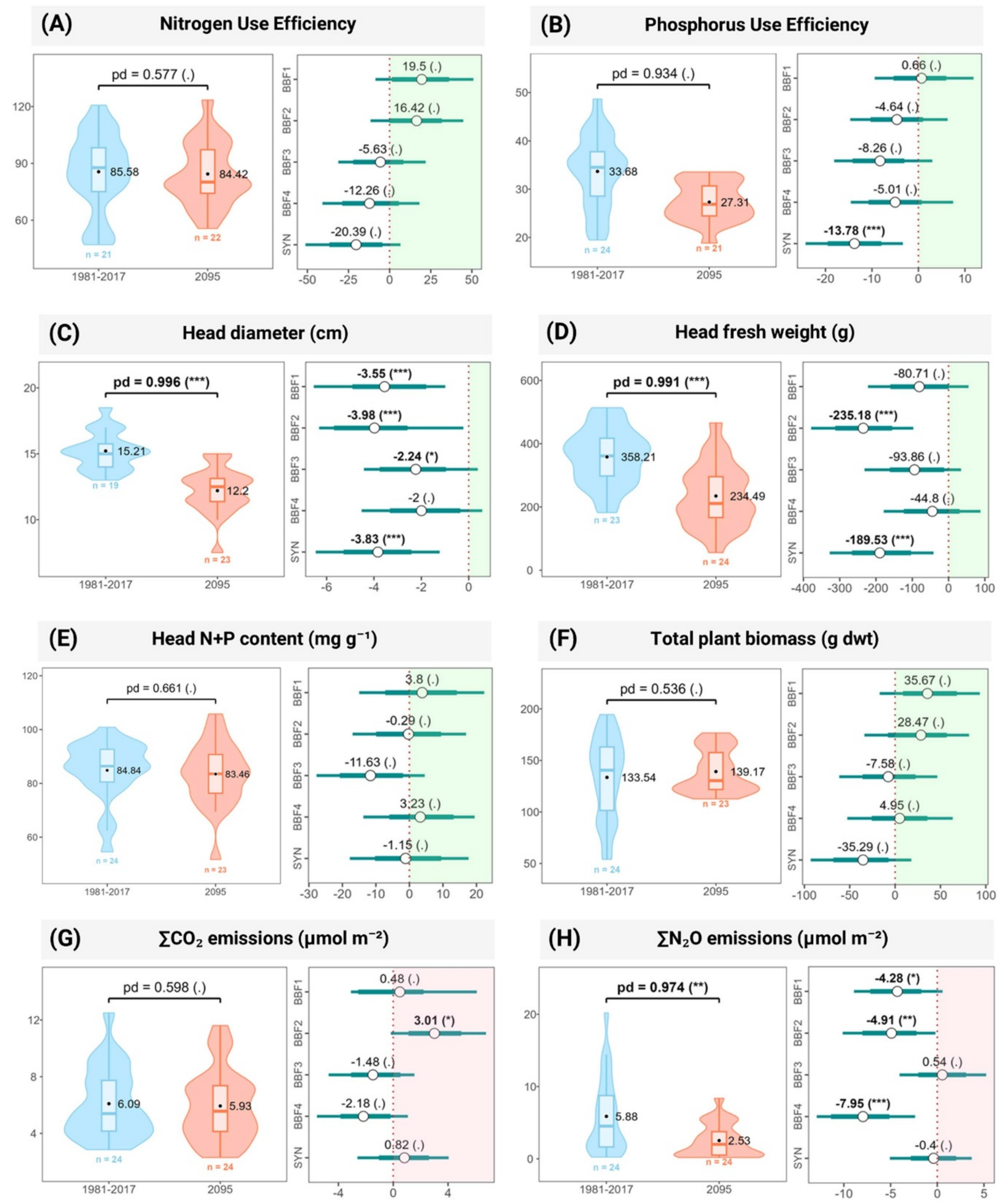

Figure 2. Climate impact on agronomic parameters and greenhouse gas emissions for each fertilizer. (A) Nitrogen use efficiency (NUE), (B) phosphorous use efficiency (PUE), (C) Head diameter (cm), (D) Head fresh weight (g), (E) Head $N + P$ content (mg g^{-1}), (F) Total plant biomass (g dry weight (dwt)), (G) Cumulative carbon dioxide (CO_2) and (H) nitrous oxide (N_2O) fluxes (μmol m^{-2}) under broccoli cultivation (*Brassica oleracea* var. *italica* cv. *Koros*) in smoothened historic climate (blue) and predicted meteorological conditions of the year 2095 (orange). For each parameter, left graphs show density distributions with embedded boxplots representing the median, interquartile range, and observed mean (black dot, annotated numerically). The probability of direction (pd) indicates the climate effect, with sample sizes (n) shown for each climate. Right graphs show effect sizes of pairwise comparisons between climates for each fertilizer. The central dot represents the difference in mean estimate with the thin and thick line representing the 95% and 75% credible intervals. Mean values are higher in the future than in the historic reference climate when they are in the green-shaded area for plant performance parameter (A)–(F) and in the red-shaded area for CO_2 and N_2O (G–H). For each comparison, the probability of direction (pd) is indicated with asterisk according to effect existence levels **(****) certain** ($pd > 0.999$), **(***) probable** ($pd > 0.99$), **(**) likely** ($pd > 0.97$), **(*) possible** ($pd > 0.95$), (.) uncertain ($pd \leqslant 0.95$).

3.3. Nitrate availability and soil microbial activity

Plant-available soil nitrate, measured as soluble NO_3^- (aq.) in interstitial soil pore water throughout the crop growth season, was on average increased in the 2095 climate as compared to the historic reference climate (+0.04 g kg^{-1} $CI_{95}[-0.01, +0.09]$, $pd = 0.964$). Little differences were observed between fertilizers in either climate, except for BBF1 for which higher NO_3^- was measured in the future climate

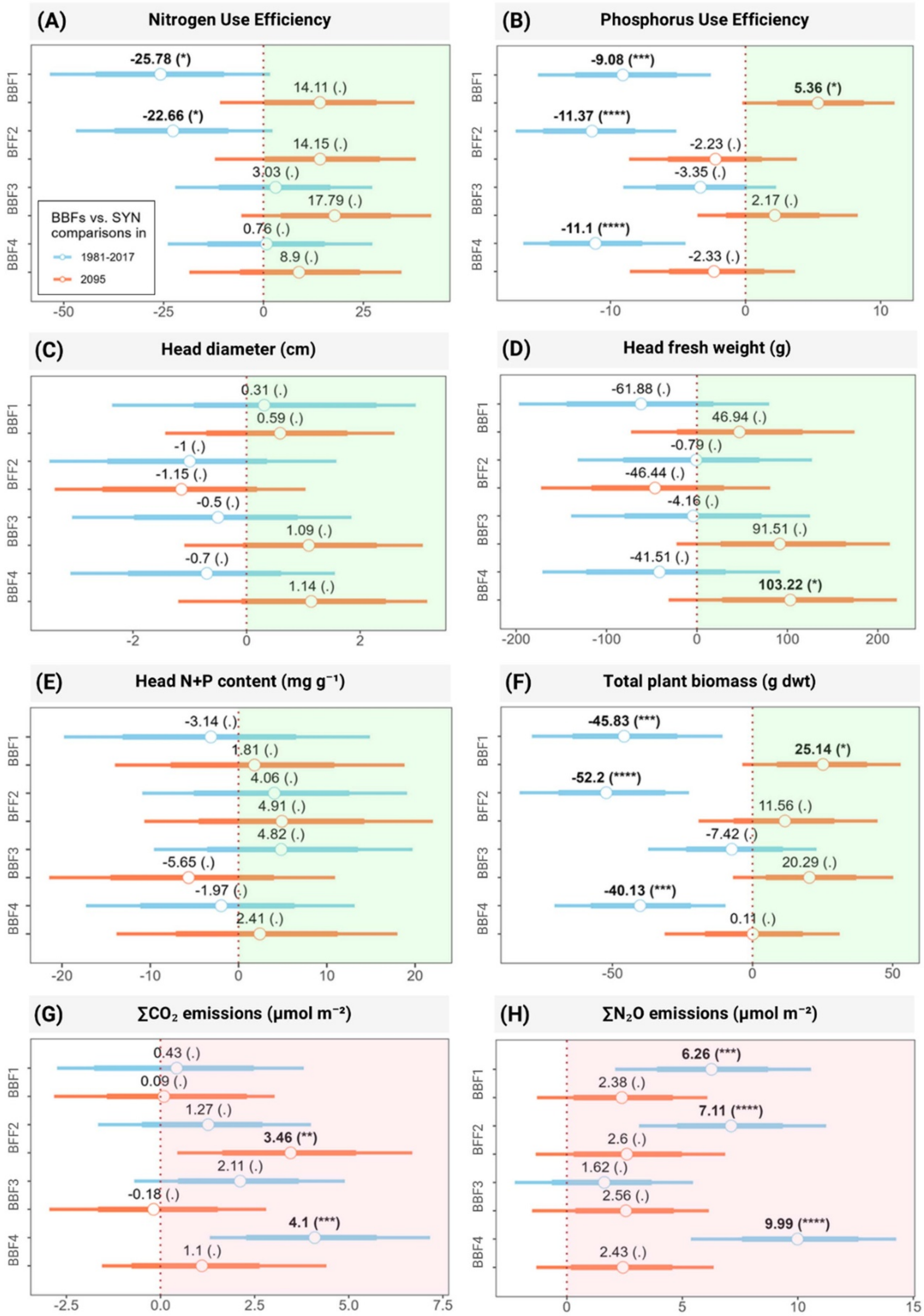

Figure 3. Pairwise comparisons between each of four bio-based fertilizers and the synthetic fertilizer (BBF1-4 x SYN) in the two climate scenarios. (A) Nitrogen use efficiency (NUE), (B) phosphorous use efficiency (PUE), (C) Head diameter (cm), (D) Head fresh weight (g), (E) Head $N + P$ content (mg g^{-1}), (F) Total plant biomass (g dry weight (dwt)), (G) Cumulative carbon dioxide (CO_2) and (H) nitrous oxide (N_2O) fluxes (μmol m^{-2}) under broccoli cultivation (*Brassica oleracea* var. *italica* cv. *Koros*) in smoothened historic climate (blue) and predicted meteorological conditions of the year 2095 (orange). Panels show effect sizes of pair-wise comparisons for each BBF with the synthetic control fertilizer (SYN), the value provided corresponds to the mean effect of BBF compared to SYN on respective parameter under respective climate. If the comparison is in the green shaded area, the BBF performs better than SYN. For example, broccoli fertilized with BBF1 yielded on average +0.31 cm larger heads than broccoli fertilized with SYN in the historic reference climate, and +0.59 cm larger heads in the future climate. If the values fall in the red-shaded area for CO_2 and N_2O (G–H), the emissions are higher for BBFs compared to SYN. For each pair-wise comparison, the central dot represents the difference in mean estimate, the thin and thick line represents the 95% and 75% credible intervals. For each pair-wise comparison, the probability of direction (pd) is indicated with asterisk according to effect existence levels **(****) certain** ($pd > 0.999$), **(***) probable** ($pd > 0.99$), **(**) likely** ($pd > 0.97$), **(*) possible** ($pd > 0.95$), (.) uncertain ($pd \leqslant 0.95$). See SM6 for all possible pair-wise comparisons across treatments in each climate.

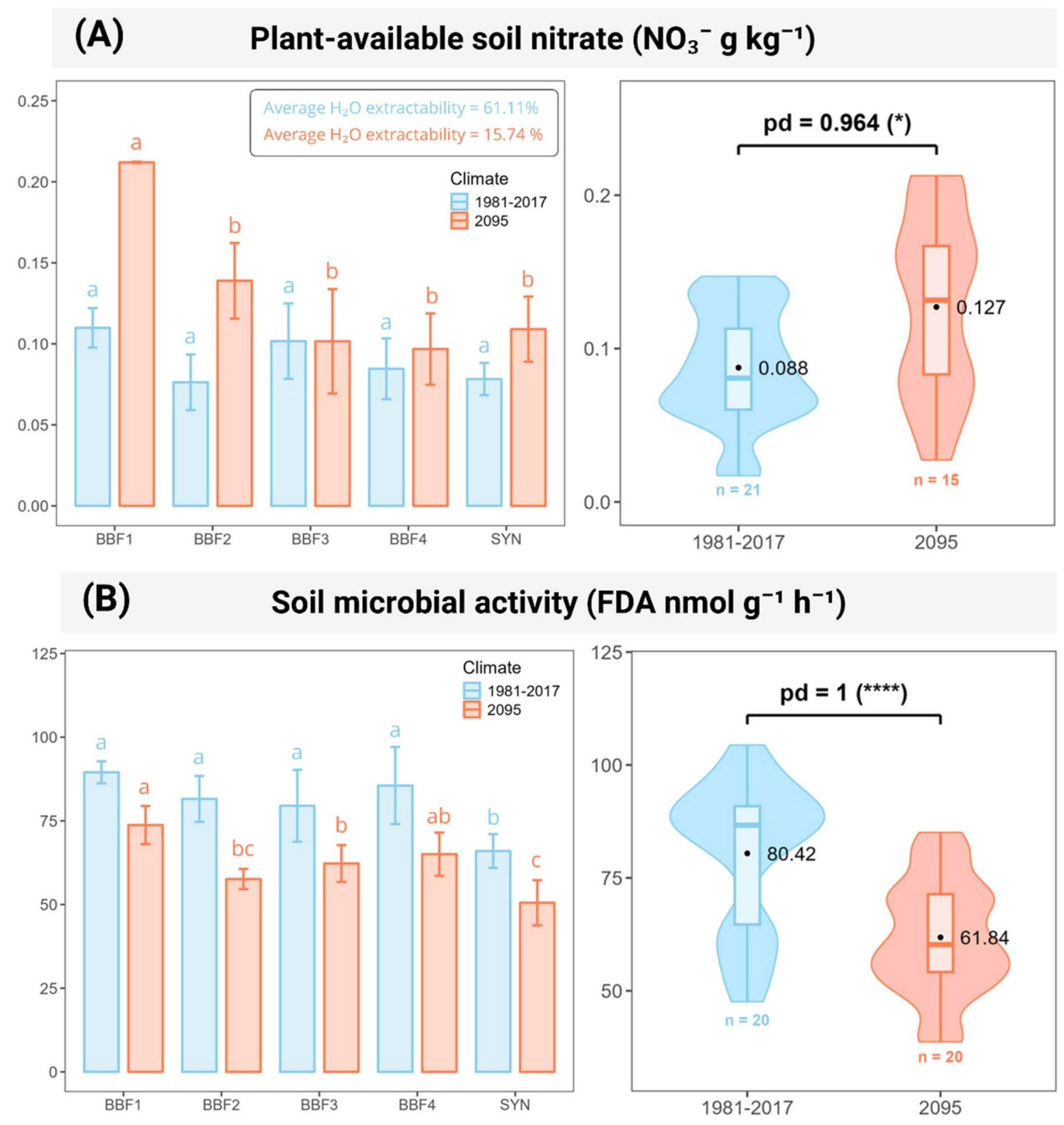

Figure 4. (A) Average plant-available soil nitrate (NO_3^-) and (B) microbial activity as estimated by enzymatic activity measured as emitted fluorescein, both under the reference (blue) and future (orange) climate scenario. Left graphs show mean (±SE) with letters indicating significant differences between fertilizer treatments within each climate based on pair-wise comparisons (SM6). Average extractability of interstitial soil pore water where nitrate was measured is given in left graph (A). Right graphs show density distributions of all measurements in each climate with embedded boxplots representing the median, interquartile range, and observed mean (black dot, annotated numerically) and asterisks indicating effect existence levels based on the probability of direction (pd): (****) certain and (*) possible.

(figure 4(A)). However, this observation has to be seen in context of the different rainfall patterns in the two climates (figure 1(B)) and the resulting differences in soil moisture and matric potential and resulting water extractability from the soil matrix which affected the temporal resolution of nitrate measurements (SM1-2). Overall, while nitrate concentrations in interstitial soil pore water were higher in the future climate, water extractability per se was lower in the drier 2095 climate (15.74%) compared to the control climate (61.11%). Microbial activity, quantified as hydrolysis of FDA, overall declined under the future climate (figure 4(B)). In both climate scenarios, soils in cropping systems fertilized with BBFs had higher microbial activity than those under SYN.

4. Discussion

4.1. Increased potential of several BBFs in future climate

The four different BBFs tested in this study showed variable sensitivity to the future climate with both improvements and deteriorations amongst the agronomic parameters. Meanwhile, the synthetic fertilizer was consistently negatively impacted by the future climate for agronomic parameter with no clear trend for GHG emissions (figure 2). Thus, the gap in agronomic performance between SYN and BBFs was closed or even reversed in the future climate scenario. Notably, BBF1 (liquid shellfish/fish hydrolysates) and BBF3 (NPK slurry solution with amino acids from fish viscera) displayed enhanced performance in key parameters such as total biomass and broccoli head fresh weight when compared to SYN under the future climate (figure 3). This observation could suggest that liquid and amino-acid rich formulations are most suited for crop growth under future climate conditions. However, the biggest increase in head fresh weight in the future climate was achieved with BBF4 (fish sludge pellet), which otherwise had no significant difference to SYN in agronomic performance or GHGs and is by these means a promising substitute, suggesting that pelleted forms of such BBFs might timely release nutrients without exacerbating losses under harsher climate conditions. Conversely, in this experiment BBF2 (solid protein fraction) tended to be overall the least effective fertilizer compared to SYN with the highest number of reduced plant performance parameters and the lowest microbial activity of all here tested BBFs (figures 3 and 4(B)). Yet, overall, BBFs positively impacted crop growth in this study, especially under future climate conditions. This is in line with previous experiments evaluating the use of BBFs with horticultural and cereal crops. For example, it has been shown that combining BBFs with microbial inoculation can significantly increase yields of tomato plants compared to synthetic fertilizer (Clagnan *et al* 2023) and in a two-year crop cycle of winter wheat and ryegrass, commercially available BBFs reached 47%–80% replacement value for nitrogen and 105%–161% for phosphorous (Müller *et al* 2024). This is partly in line with the results of this study, where fertilizer addition rates were normalized to 120 kg N ha^{-1} for all treatments, which resulted in lower NUE in broccoli plants fertilized with BBF1 and BBF2 compared to SYN in the historic reference climate (figure 3(A)). However, NUE in the future climate was systematically increased for all BBFs compared to SYN, with a similar trend observed for phosphorous (figure 3(B)). This demonstrates the improved market potential of BBFs under future climates and highlights their potential role in sustainable and circular agricultural production in the future. Mechanistically, the superior (i.e. less climate-impacted) performance of BBFs compared to the synthetic nutrient solution under the projected future climate condition likely does not stem from higher total nutrient contents per se but from a combination of (i) temporally better synchronized N supply, (ii) improved structural stability and water retention, (iii) enhanced microbial mineralization capacity, and (iv) reduced nutrient losses from leaching. These characteristics of BBFs are particularly valuable in climates characterized by higher temperatures and more extreme rainfall patterns, which can exacerbate nutrient losses (Edmeades 2003).

4.2. Addressing the climate-induced yield penalty

Climate-induced yield penalties and crop failures are one of the grand challenges faced by humankind (Wing *et al* 2021, EC, 2024b). This study further confirms consistent declines in yield under future climate and especially highlights worsened consumer-relevant parameters such as broccoli fresh weight and head diameter across all fertilizer treatments, including synthetic fertilizer (figure 2). These observations are in line with a modeling study which predicted that the climatic conditions expected under the RCP8.5 would exceed the capacity of broccoli plants to adapt, highlighting in particular growth inhibition and reduction in plant vigor with a major impact on yield (Pineda *et al* 2024). Similar observations have been made for broccoli in the field. For example, during the strong summer drought after the wet spring in 2018, the Irish horticultural sector lost 15% of its broccoli production to poor plant development and crop failures where no irrigation was available (Grove 2019). Fertilizer optimization, together with improved irrigation systems, can play a critical role in mitigating such yield losses. Especially BBFs in pelleted and slurry formulations can release nutrients slowly and thus be more effective during seasons with more intense rain and drought events (Lawrencia *et al* 2021, Müller *et al* 2024). However, the efficiency of BBFs also depends on the capacity of the soil microbial communities to degrade the biomolecules and release their mineral elements (Chaturvedi and Kumar 2012, Clagnan *et al* 2023). In favorable pedo-climatic contexts, BBFs can enhance soil microbial activity and physical characteristics and thus help maintain crop productivity even under stress conditions (Chaturvedi and Kumar 2012, Wester-Larsen *et al* 2024). Further fine-tuning the interactions between BBFs, crop species and microbial communities, combined with advanced irrigation technologies, are hence promising pathways to address climate-induced yield losses while increasing nutrient retention in the cropping system and improving the environmental footprint (Cui *et al* 2018, Clagnan *et al* 2023). It could also be valuable to further explore BBFs which can enhance the nutrient content in harvested products, including essential elements like potassium and iron, as well as vitamins, and if certain crop species (feat. their microbiomes) are more suitable for bio-based fertilization than others.

4.3. Impact of BBFs on carbon and nitrogen cycling

Under both climate scenarios, the systems under BBFs tended to emit more CO_2 and N_2O than cropping systems under SYN, in line with the enhanced soil microbial activity observed in BBF systems (figures 3(G), (H) and 4(B)). While it is generally predicted that N_2O emissions from agricultural land will increase in the future (Hui *et al* 2024), in this experiment, overall decreased N_2O fluxes were observed in the future climate (figure 2(F)). This is very likely due to the drier soil conditions in the future climate (figure 1(B), SM1), which has been previously linked to reduced soil N_2O emissions (Harris *et al* 2021, Xia *et al* 2023). Here, the altered rainfall pattern in the future climate notably reduced soil moisture content and matric potential, and thus physically impacted nitrogen mobility within the system (figure 4(A)). In addition, soil moisture regulates oxygen availability, which influences the balance between nitrification and denitrification, with lower moisture levels generally reducing denitrification and thus decreasing N₂O emissions (Wang *et al* 2021, 2023). Yet, NUE was not significantly affected by climate, with variable effect direction depending on fertilizer, suggesting compensatory mechanisms of plant nutrient uptake at plant and/or microbial level (figures 2(A) and 3(A)). In the here studied cropping systems, nitrogen cycling could also have benefitted from biological nitrification inhibition, a process well documented in *Brassicaceae* like broccoli, which can release compounds that inhibit the activity of nitrifying bacteria, thereby slowing down the conversion of ammonium (NH^{4+}) to nitrate (NO^{3-}) which increases N-retention in the system (Lam *et al* 2017, Balvert *et al* 2018). Regarding the risk of additional agricultural CO_2-emissions from systems fertilized with BBFs, these could potentially be offset through enhanced soil organic carbon accumulation (Smith *et al* 2007), particularly in microbial necromass (Zhou *et al* 2023, Kong *et al* 2024). However, organic amendments primarily enhance lighter soil carbon fractions like dissolved organic carbon (DOC), which need to be stabilized through mineral binding to improve carbon sequestration in the long-term, which requires sufficient free mineral binding sides in the soil (Cotrufo *et al* 2019, Wu *et al* 2024). The FDA measurements in this study further suggest that BBFs stimulate microbial activity more than the synthetic nutrient solution, which contributes to the continuous slow release of nutrients and can thus benefit crop growth while reducing nutrient leaching (figure 4(B)). Future studies could investigate this further to eradicate if certain microbial taxa combine particularly well with the degradation of certain BBFs to catalyze their mineralization. For example, combining BBFs with Bacillus spp. in pear orchards increased N uptake by 30% and yield by 20%–25% via sustained release (Wang *et al* 2022).

4.4. BBFs and sustainable soil resource management

Organic fertilizers such as crop residues and livestock manure are foundational in regenerative agriculture, particularly for their positive effects on soil organic matter and to reverse soil erosion (Rosen and Allan 2007, Ren *et al* 2023). However, their nutrient release is often asynchronous with crop demands because not all organic N is mineralized during the months following application, necessitating synthetic supplementation in mixed systems to avoid yield penalties (Evanylo *et al* 2008, Geisseler *et al* 2021, Liu *et al* 2021, Ren *et al* 2023, Niu *et al* 2024, Michel *et al* 2025). BBFs with more easily available nutrient fractions such as amino acid extracts from fish viscera or slurries offer faster N-release than manure or crop residues and could thus be used as catalysators in hybrid applications (Zhang *et al* 2023, Rathod *et al* 2024). While considerable variability exists across different batches, BFFs from fishery waste also tend to have on average higher N and P contents compared to organic fertilizers from crop residues or livestock manure (Villamil *et al* 2017, Zhang *et al* 2023, Rathod *et al* 2024), so that they can be used as individual applications sustaining crop growth without the need of additional synthetic inputs. A recent experiment testing BBFs from fishery waste in broccoli production in the field for example found that fertilization with BBFs at 120 kg N ha^{-1} equivalents maintained crop production and limited leaching risk (Zhang *et al* 2025). However, the implementation of BBFs from fishery waste in agronomic crop production remains challenging because they are not as low-cost and on-site as crop residues or manure, and because of their variable nutrient contents which necessitate more logistical efforts to match the nutrient offer in fertilizer batches with the demand of the crops in season (Chojnacka *et al* 2020, Priya *et al* 2023).

4.5. Importance of empirical data on crop growth under future meteorological conditions

This study revealed a complex interplay between climate and fertilizers, with some results confirming modeling estimates (e.g. climate-induced yield penalties) and some results contradicting modeled projections (e.g. reduced N_2O-emissions under future climate). These findings highlight the importance of empirical data to anticipate the impact of climate change on cropping systems and constrain the uncertainty of future predictions. In this study, the reference climate scenario was constructed by averaging daily environmental data over a historical baseline, a standard practice in crop-climate simulations to establish a stable benchmark for yield calibration and to isolate long-term trends from short-term noise (Jones *et al* 2011, Rosenzweig *et al* 2014). This approach effectively eliminates interannual variability which characterizes the actual historical period, resulting in a smoothed representation of growing conditions that differs from the high-variability prediction for 2095 under the RCP8.5 scenario (figure 1). Consequently, the reference yields may underestimate risks like yield volatility from climate variability in the past, potentially amplifying the yield drop in the future scenario. While this approach is in line was the forecast of increasing frequency of more extreme weather events, future work could incorporate multiple past and future climate scenarios to better capture climate variability in both past and future years (Nissan *et al* 2019, Timlin *et al* 2024).

4.6. Future studies

To holistically access the environmental impact and economic viability of BBFs, further research could also take the production processes and related resource and energy use into account (Egas *et al* 2023). To further improve the effectiveness of BBFs in crop production, the influence of fertilizer composition (liquid, slurry, pellet) on plant nutrient uptake under different pedo-climatic context could be investigated, as well as different combinations of BBFs and crop species and varieties. As plant breeding advances, cultivars could be selected not only for their resilience to climate change, but also for their compatibility with BBFs (Kopeć 2024). To increase the robustness of BBF implementation, future research could therefore investigate variety × soil × management × season interactions, as these have been shown to affect agronomic and quality parameters (Bakker *et al* 2008, Renaud *et al* 2014, Ordiales *et al* 2017). Integrating climate resilience and cropping system compatibility into fertilizer development could help anticipate potential fertilizer weaknesses and develop formulations which meet the dual challenge of maintaining agricultural productivity and reducing environmental harm. To ensure resilient crop production under future climatic conditions, it is therefore essential to consider the multifactorial nature of climate change and dynamic interactions between fertilizers, plants, soils and soil organisms (Kreyling and Beier 2013).

5. Conclusion

Addressing climate-induced yield penalties and improving the environmental footprint of fertilizers will be critical to achieve the goals of the Paris Agreement and ensure food security under challenging environmental conditions. This study demonstrates the feasibility of BBFs as agronomically performant alternatives to SYN, with most BBFs achieving yields comparable to yields under SYN, particularly under the future climate scenario. However, the efficiency of BBFs under diverse pedo-climatic contexts warrants further study to ensure upscaling efforts align with regional crop production systems. To further optimize BBFs, the impact of fertilizer composition (liquid, slurry, pellet) on nutrient release dynamics under different climate and soil conditions could be investigated, as well as fertilizer × cultivar interactions to test the robustness of these findings across genetic backgrounds.

Data availability

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.6084/m9.figshare.28609055.

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