



## Sustainable nitrogen management in maize: environmental benefits of integrating microbial biostimulants and nitrification inhibitors

Filippo Vigo <sup>a</sup>, Michele Zoli <sup>a,\*</sup>, Jessica Murelli <sup>b</sup>, Jacopo Bacenetti <sup>a</sup>

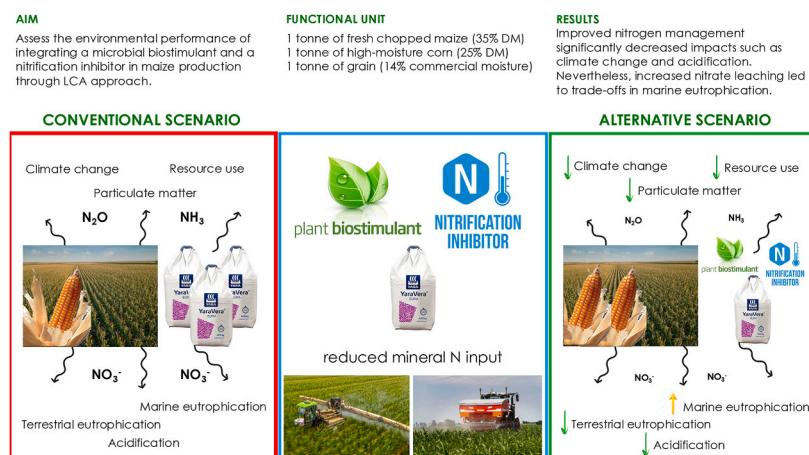
<sup>a</sup> Department of Environmental Science and Policy, Università degli Studi di Milano, via G. Celoria 2, Milano, 20133, Italy

<sup>b</sup> Pioneer Hi-Bred Italia S.R.L., Via Pari Opportunità 2, Gadesco Pieve Delmona, CR, 26030, Italy

### HIGHLIGHTS

- Farm-scale LCA compares nitrogen-management scenarios in maize production.
- Combined practices generally reduce impacts, with variability among farms.
- Trade-offs arise in nitrogen-driven categories depending on emission pathways.

### GRAPHICAL ABSTRACT



### ARTICLE INFO

#### Keywords:

Life cycle assessment  
Nitrogen emissions  
Environmental benefit  
Sustainable fertilization

### ABSTRACT

Biostimulants and nitrification inhibitors are promising tools to improve nitrogen dynamics in agricultural soils and reduce associated environmental impacts. In Europe, these solutions are increasingly promoted to improve nitrogen use efficiency and losses, yet farm-level evidence of their combined environmental performance in maize remains limited. This study evaluated whether applying a microbial biostimulant (*Methylobacterium symbioticum* SB23) with a nitrapyrin-based nitrification inhibitor can mitigate the environmental impacts of maize in Italy. A cradle-to-farm-gate LCA was performed on 14 farms, comparing a conventional scenario (CS) with an alternative scenario (AS) applying the two products while reducing mineral N fertilization. Three functional units were assessed: 1 tonne maize grain (14% moisture), 1 tonne high-moisture corn (25% DM), and 1 tonne fresh chopped maize (35% DM). Inventory modelling combined primary on-farm data from questionnaires and interviews with secondary data, including Brentrup's N balance for N emissions. Across farms and functional units, AS generally lowered nitrogen-driven categories, climate change, acidification, particulate matter formation, and terrestrial eutrophication, reflecting reduced mineral N inputs and inhibited nitrification. For grain, 10 of 11 impact categories decreased (−2% to −50%); for high-moisture corn, 8 of 11 decreased (−1%

\* Corresponding author.

E-mail address: [michele.zoli@unimi.it](mailto:michele.zoli@unimi.it) (M. Zoli).

to -87%); and for silage, 10 of 11 decreased (-1% to -83%). Trade-offs emerged: marine eutrophication occasionally increased where fertilizer reductions were limited and the biostimulant enhanced soil N availability, increasing NO<sub>3</sub><sup>-</sup> leaching. Contribution analysis confirmed category hotspots: NH<sub>3</sub> volatilization for acidification, particulate matter, and terrestrial eutrophication, N<sub>2</sub>O for climate change, NO<sub>3</sub><sup>-</sup> leaching for marine eutrophication, and crop protection products for freshwater ecotoxicity.

Overall, integrating a microbial biostimulant with a nitrification inhibitor can substantially reduce most impacts of maize cultivation.

## 1. Introduction

The environmental impact of maize cultivation depends on many factors, including crop yields, irrigation techniques, the use of machinery and agrochemicals, but above all the management of mineral fertilizers. Nitrogen fertilization is the main source of negative impacts throughout the crop's life cycle, due to upstream production processes and field emissions (Shao et al., 2024; Xu et al., 2024).

In this context, biostimulants and nitrogen inhibitors have emerged as two promising tools that are reshaping plant nutrition and nitrogen management in modern agriculture (Bouhzam et al., 2025; Yao et al., 2022; Ocwa et al., 2024). Biostimulants enhance nutrient uptake, tolerance to abiotic stress, and crop quality, independently of the product's nutrient content (Patrick du Jardin, 2015; Rouphael and Colla, 2020). The microbial biostimulant used is based on a patented strain of *Methylobacterium symbioticum* SB23 that fixes atmospheric nitrogen and makes it available to the plant. This contributes to reducing synthetic nitrogen inputs and associated environmental losses (Corteva Agriscience, 2023). When applied either to plants or to the rhizosphere, they can enhance the natural ability of plants to withstand abiotic stresses and promote higher yields; improve the efficiency of nutrient use (Calia et al. 2025).

In parallel, the nitrification inhibitor offers an effective strategy to slow down the nitrification of ammoniacal fertilizers in the soil. The active ingredient, nitrapyrin, inhibits nitrifying bacteria (*Nitrosomonas* spp.), thereby reducing the conversion of ammonium to nitrate and minimising nitrogen losses through leaching and denitrification (Subbarao et al., 2006; Dell et al., 2020). This approach is particularly valuable in Italian soils, which are often subject to irregular rainfall and high leaching potential, and contributes to more efficient and environmentally responsible fertilization.

In Europe and globally, the interest in such products has significantly increased, driven by European regulations, such as EU Regulation 2019/1009 on fertilizing products, that promote the adoption of sustainable agricultural practices. In Italy as well, the use of biostimulants and nitrification inhibitors has risen sharply in recent years, encouraged by public and private research initiatives as well as by policy efforts aimed at environmental sustainability and climate resilience (ISMEA, 2023).

The increasing adoption of these solutions is also supported by European policies promoting more sustainable agricultural practices with the "Farm to Fork Strategy" (EC 2020).

The integration of biostimulants and nitrification inhibitor into modern fertilization strategies presents a real opportunity to reduce the environmental impact of nitrogen fertilization, improve crop yields, and promote an efficient and sustainable agricultural model.

Nevertheless, although biostimulants have the potential to substitute or complement chemical fertilizers while enhancing crop productivity, their environmental sustainability must also be carefully addressed. For this purpose, Life Cycle Assessment (LCA) is a globally recognized scientific method for evaluating environmental sustainability. It provides an integrated framework for analyzing the environmental performance of products, services, and processes across diverse sectors, with broad application in agriculture, by considering each stage of a product's life cycle, from raw material extraction to production, use, and final disposal or recycling.

In the agricultural context, LCA is increasingly recognized as a

decision-making tool for communicating environmental information and evaluating scenario-based improvements in production systems (i Losada et al., 2025). It has already been applied to various crops such as barley (Stylianou et al., 2023; Tricase et al., 2018), rice (Mahmood et al., 2023; Ahmad et al., 2023; Zoli et al., 2021) and wheat (Giongo et al., 2025; Fallahpour et al., 2012), as well as to precision agriculture (Bahmutsky et al., 2024), and, specifically, focusing on maize to evaluate different fertilization strategies (Costantini et al., 2023; Zucaro et al., 2014; Cheng et al., 2025) and several irrigation methods (Vigo et al., 2025). Previous studies have evaluated improved nitrogen management strategies, including enhanced-efficiency fertilizers and nitrification inhibitors, highlighting their potential to reduce nitrogen losses and associated environmental impacts. A meta-analysis by Akiyama et al. (2010) showed that nitrification inhibitors can reduce N<sub>2</sub>O emissions by approximately 38% on average and NO emissions by up to 46%, confirming their effectiveness as mitigation strategies under different agricultural conditions. Similarly, Brenttrup et al. (2004), applying an LCA approach to wheat production systems, demonstrated that nitrogen fertilization strongly influences environmental impacts, with excessive N application leading to significant increases in eutrophication and greenhouse gas emissions, while optimal fertilization rates can minimize impacts per unit of product. In parallel, biostimulants have gained increasing attention as tools to improve nutrient use efficiency and crop performance, with several studies reporting enhanced plant growth, nutrient uptake, and tolerance to abiotic stress, ultimately contributing to increased crop productivity and resource use efficiency (Rouphael and Colla, 2020). However, despite the growing interest in biostimulants and nitrification inhibitors, studies have mainly assessed these technologies separately, and no LCA studies are available on their combined environmental performance under real farm conditions, particularly in maize cultivation, where nitrogen management plays a key role in determining environmental impacts.

We hypothesize that the combined application of a microbial biostimulant and a nitrification inhibitor can improve nitrogen use efficiency and reduce overall environmental impacts, without compromising crop yield.

The aim of the study is to compare, from an environmental point of view, two maize cultivation scenarios: a conventional scenario (CS), representing the standard agricultural practices commonly adopted on farms, and an alternative scenario (AS), in which (i) a biostimulant and (ii) a nitrification inhibitor are applied, with a reduced or unchanged use of mineral and organic fertilizers, with a fertilization plan calibrated field by field based on soil, digestate and manure analysis. The analysis evaluates the effectiveness of this innovative approach in mitigating environmental impacts while maintaining crop yield.

## 2. Materials and methods

The Life Cycle Assessment (LCA) approach was applied to evaluate the potential environmental impacts associated with the use of the biostimulant and the nitrification inhibitor in maize cultivation on Italian farms, in accordance with ISO 14040 and ISO 14044 standards (ISO 14040, 2006a; ISO 14040, 2006b), and following the Product Category Rules (PCR 2020:07) for arable and vegetable crops, available at [www.environdec.com](http://www.environdec.com), which provide specific guidelines for applying LCA to this product category.

## 2.1. Goal and scope definition

This LCA study aimed to identify environmental benefits in maize production using a combination of a biostimulant and a nitrification inhibitor, reducing or eliminating mineral nitrogen fertilization. The 14 farms considered in this study were selected across key maize-growing regions of Italy, where favorable conditions such as abundant water availability for irrigation and an efficient canal network strongly support maize production. Most of the farms are in Piedmont, Lombardy, Veneto, and Emilia-Romagna, areas with a long-standing tradition and strong specialization in maize cultivation. Table 1 shows the coordinates of the 14 farms with the final product obtained from each of them, while Fig. 1 shows their location on the Italy map.

Data were collected over two consecutive years (2023 and 2024), allowing the assessment of seasonal variability and providing evidence for comparison. The selected farms and regions are characterized by fertile, well-drained soils and optimal agro-climatic conditions for maize, as well as extensive farmer expertise built up over decades of cultivation. This background ensures that any potential improvements or drawbacks associated with alternative practices can be reliably evaluated. Research of this kind plays a pivotal role in strengthening the understanding of biostimulant and nitrification inhibitor impacts among diverse actors within the agricultural sector, including farmers, producers, policymakers, and other decision-makers. Regarding the environmental benefit, such studies support informed choices and foster broader adoption of biostimulants as tools for enhancing both productivity and sustainability in modern agroecosystems.

## 2.2. Functional unit

The functional unit (FU) is defined as a quantified performance of a product system to be used as a reference unit in an LCA (ISO 14040, 2006). The mass-based FU is the most commonly used in agricultural LCA studies (Vatsanidou et al., 2025; David et al., 2025; Detzel et al., 2022; Noya et al., 2015), as it is accepted that the main function of a

**Table 1**

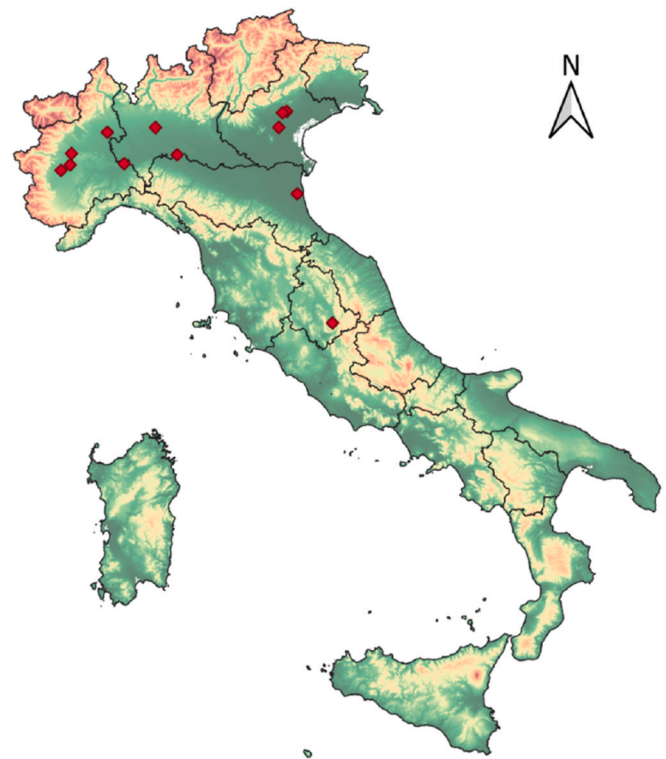
Geographic location (coordinates and municipality) and type of maize product obtained in the 14 farms considered in the study.

Farm	Location	Product
1	45°00'N 8°48'E 45°00'N, 8°48'E - Alluvioni Piovera (AL)	maize grain <sup>a</sup>
2	45°08'N 7°46'E 45°08'N, 7°46'E - Settimo Torinese (TO)	high-moisture corn <sup>b</sup>
3	45°26'N 8°28'E 45°26'N, 8°28'E - Casalbeltrame (NO)	fresh chopped maize <sup>c</sup>
4	45°30'N 9°25'E 45°30'N, 9°25'E - Melzo (MI)	maize grain
5	42°44'N 12°44'E 42°44'N, 12°44'E - Spoleto (PG)	fresh chopped maize
6	45°07'11"N 9°50'17"E 45°07'11"N, 9°50'17"E - Meleti (LO)	fresh chopped maize
7	44°58'37.65"N 7°44'37.69"E 44°58'37.65"N, 7°44'37.69"E - Trofarello (TO)	maize grain
8	44°32'17.59"N 12°09'42.88"E 44°32'17.59"N, 12°09'42.88"E - Sant Alberto (RA)	fresh chopped maize
9	44°32'17.59"N 12°09'42.88"E 44°32'17.59"N, 12°09'42.88"E - Sant Alberto (RA)	high-moisture corn
10	45°41'N 12°01'E 45°41'N, 12°01'E - Vadelago (TV)	fresh chopped maize
11	45°40'N 11°56'E 45°40'N, 11°56'E - Castelfranco Veneto (TV)	fresh chopped maize
12	45°40'N 11°56'E 45°40'N, 11°56'E - Castelfranco Veneto (TV)	fresh chopped maize
13	44°53'53.31"N 7°33'58.04"E 44°53'53.31"N, 7°33'58.04"E - Castagnole Piemonte (TO)	fresh chopped maize
14	45°28'N 11°51'E 45°28'N, 11°51'E - Limena (PD)	fresh chopped maize

<sup>a</sup> Grain moisture content: 14%.

<sup>b</sup> High-moisture corn dry matter content: 25%.

<sup>c</sup> Fresh chopped maize dry matter content: 35%.



**Fig. 1.** Location of farms in Italy.

single crop (at farm gate) is to provide a certain quantity of a given product.

In this study, the functional unit selected is the mass of the final product, which, depending on the specific farm. In this way, it allows capturing differences in environmental performance depending on the intended use of the product and improves the representativeness of the results across diverse farming contexts.

The following functional units were applied:

- 1 tonne of fresh chopped maize with 35% of dry matter content;
- 1 tonne of high-moisture corn (HMC) with 25% of dry matter content;
- 1 tonne of grain at commercial moisture (14%).

## 2.3. System boundary

In this study, a “from cradle-to-farm-gate” perspective was considered regarding the system boundaries (Fig. 2). Consequently, all processes were considered starting from the extraction of raw materials and the manufacturing of agricultural inputs up to crop harvesting and the transport of the harvested maize to the farm gate. In more detail, the following steps were considered: production and distribution of inputs (e.g., seeds, fertilizers, crop protection products, agricultural machinery), field operations (soil preparation, fertilization, crop protection products application, irrigation, fuel use, and emissions related to these activities), as well as the maintenance and end-of-life of machinery. Operations that take place after transport, such as silage storage, distribution, product use, and end-of-life treatment, are not included in the system boundaries. Emissions associated with fuel consumption, crop protection products application, and the use of mineral and organic fertilizers were quantified and incorporated into the assessment. According to the Product Category Rules for “Arable and vegetable crops” (EPD international, 2020:07) and given that the fields had been continuously cultivated with maize for more than 20 years, no changes in soil organic carbon content were accounted for.

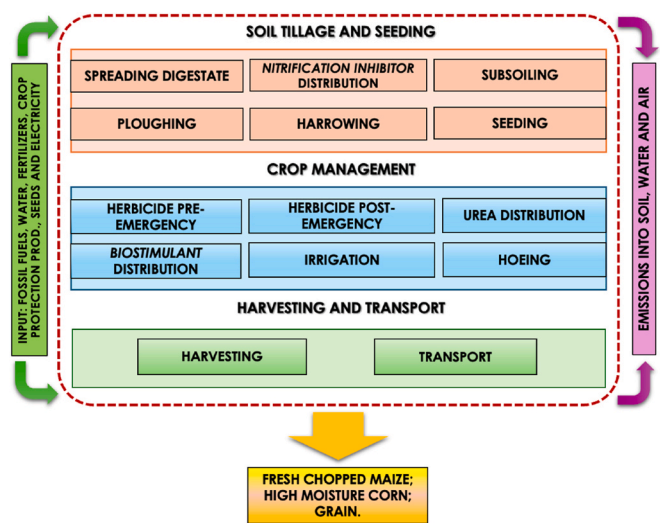


Fig. 2. System boundaries using a “cradle-to-farm gate” approach for the 14 farms considered. The figure shows all inputs consumed, all field operations, emissions and final products obtained.

In general, maize cultivation on the 14 farms comprised a sequence of field operations that can be grouped into three main stages:

Stage 1: Soil tillage and seeding. In most cases, organic fertilization was the first operation, typically carried out by spreading digestate or manure with a tanker. In the alternative scenario of this study, a nitrification inhibitor was added to the liquid organic fertilizer. Thereafter, ploughing represented one of the primary operations in maize cultivation. It was performed using a moldboard plough (30 cm depth) to incorporate the crop residues from the previous growing season into the soil. Subsequently, the seedbed was prepared either by harrowing with a rotary harrow or by using a fixed-tooth harrow operating at a depth of 10–15 cm. Sowing was then carried out with a precision seed drill.

Stage 2: Crop management. This phase included chemical weed and disease control, as well as mineral fertilization with urea. In the alternative scenario, the application of a biostimulant was introduced, either completely replacing urea or reducing the amount

applied. Irrigation also played a fundamental role in maize cultivation during this stage.

Stage 3: Harvesting and transport. On the 14 farms, harvesting could be carried out in two ways: either with a self-propelled forage harvester loading simultaneously into a trailer when the final product was fresh chopped maize or high-moisture corn, or with a combine harvester when the final product was grain. For all three final products, transport from the field to the farm center was considered, with an average distance ranging from 1 to 15 km across the studied farms. Maize stalks were left on the field.

2.4. Inventory data collection

Primary data were collected directly through surveys and interviews with farmers, including the yield (reported in Table 2), the sequence of field operations, the inputs used (such as fuels, fertilizers, and plant protection products), and the technical specifications of the agricultural machinery employed for each farm (reported in Supplementary Materials, Table S1–S14).

Secondary data refers to emissions resulting from the application of various inputs (e.g., fertilizers and crop protection products) and fuel use. In detail:

- I. The emissions from fertilizer applications were estimated using the model proposed by Brentrup et al. (2000). The model balances supply and removals (losses and intake) taking into account both direct and indirect nitrogen losses through volatilization, leaching, and denitrification, considering nitrogen uptake by crops and input through organic and mineral fertilization as the main reservoir, thus providing a complete balance of nitrogen inputs and outputs in the soil. This model requires input of several parameters, including the month and average temperature at the time of fertilizer application, the time interval between fertilizer spreading and soil incorporation, soil characteristics (e.g., texture, pH and groundwater depth), summer and autumn precipitation, the presence of crop residues, and the nitrogen and phosphorus content of organic and mineral fertilizers, of crop residues and the final product. All input parameters used in the Brentrup model for the 14 farms are reported in detail in Table S15 in the Supplementary Materials. Furthermore, Table 2 shows the results obtained from the model for ammonia emissions in the conventional scenario (expressed in kgNH<sub>3</sub>/ha) and the percentage difference

Table 2  
Crop yield and nitrogen emission relative variations between conventional (CS) and alternative (AS) scenarios.

Farm	Yield		Ammonia em.		Dinitrogen monoxide em.		Nitrate em.	
	CS (t/ha)	Δ	CS (kgNH <sub>3</sub> /ha)	Δ	CS (kgN <sub>2</sub> O/ha)	Δ	CS (kgNO <sub>3</sub> /ha)	Δ
1	9.3	1%	50.27	-48%	4.61	-75%	509.30	-46%
2	28.8	2%	105.5	-27%	6.7	-71%	394.2	-79%
3	77.6	4%	40.9	-41%	9.4	-59%	551.3	-37%
4	14.8	2%	16.6	-50%	4.8	-16%	184.5	26%
5	27.3	21%	59.6	0%	2.0	-51%	54.0	32%
6	54.2	10%	157.1	0%	4.7	-30%	69.1	36%
7	9.7	1%	59.6	-44%	7.5	-66%	1061.1	-25%
8	60.1	4%	79.1	-53%	10.8	-67%	1618.0	-33%
9	37.3	-7%	93.9	-92%	2.7	-58%	273.7	-79%
10	72.3	-2%	47.5	-44%	7.6	-63%	804.4	-17%
11	45.5	6%	50.3	-33%	3.4	-22%	1030.2	-13%
12	46.2	5%	43.3	-38%	3.5	-22%	1044.5	-12%
13	51.1	1%	44.2	-21%	8.2	-56%	1200.0	4%
14	24.7	1%	40.2	-33%	8.3	-58%	1566.2	1%

Yield obtained in the 14 farms for the conventional scenario (CS), while the Δ indicates the percentage change with the alternative scenario obtained using the formula:

$$\left( \frac{\text{Yield AS}}{\text{Yield CS}} - 1 \right) \cdot 100.$$

The remaining columns show the results obtained using the model developed by Brentrup et al., (2000). Each value in the conventional scenario is followed by the percentage change (Δ) in the alternative scenario obtained using this formula:  $\left( \frac{\text{Emission AS}}{\text{Emission CS}} - 1 \right) \cdot 100.$

compared to the alternative scenario. Similarly, emissions of dinitrogen monoxide (expressed in kgN<sub>2</sub>O/ha) and nitrate (expressed in kgNO<sub>3</sub>/ha) are also reported.

- II. The environmental impact of mechanization was assessed by considering diesel consumption, machinery specifications, and annual operating time. Fuel use was calculated based on the power requirements and field capacity of the equipment, following the methodology proposed by Lovarelli and Bacchetti (2017).
- III. Crop protection products emissions were estimated using the approach described by Rosenbaum et al. (2015), assuming dispersion rates of 90% to soil, 9% to air, and 1% to water, in line with the Product Category Rules (PCR) for agricultural crops (EPD International 2020:07).

The biostimulant and nitrification inhibitor were modeled considering primary data regarding the amount distributed, 0.333 kg/ha of biostimulant and 1.7 kg/ha for the nitrification inhibitor on the soil, and their composition. For biostimulants, considering the wide range of biostimulants on the market and the limited availability of data on the environmental impact of their production, the dataset “Yeast, at plant/FR U – 1 kg” (AGRIBALYSE 3, Koch P. and Salou T., 2022) was used as a proxy. This choice was based on the microbial nature of the product and the similarity in production processes, typically involving industrial fermentation.

As regards the nitrification inhibitor, however, secondary data obtained from the Ecoinvent v3.9 database (Weidema et al., 2013; Moreno Ruiz et al., 2016) referring to the production of Pyridine-compound was used, keeping in mind the content of the active ingredient declared on the label.

Regarding the biostimulant, the annual contribution was considered equivalent to 50 kg N/ha of nitrogen fertilizer units. For the nitrification inhibitor, a 51% reduction in nitrous oxide (N<sub>2</sub>O) emissions from organic fertilizers was assumed.

To evaluate the influence of the assumed nitrogen-equivalent contribution of the biostimulant on the environmental results, an additional sensitivity analysis was performed. In the alternative scenario (AS), a value of 50 kg N ha<sup>-1</sup> was considered, based on technical information provided by the product manufacturer.

In the sensitivity analysis, a lower value of 37 kg N/ha was adopted, derived from experimental results reported by Quemada et al. (2026), where the application of *Methylobacterium symbioticum* increased crop N uptake by 36–38 kg N/ha under non-fertilized conditions. This alternative value was used to test the robustness of the model results with respect to the assumed nitrogen-equivalent contribution of the biostimulant.

Background data related to the production of fertilizers, seeds, crop protection products, fuels, energy, and agricultural machinery were sourced from the Ecoinvent v3.9 database.

## 2.5. Life cycle impact assessment (LCIA)

The characterization of inventory data to potential environmental impacts was carried out using the Environmental Footprint 3.1 (adapted) (Fazio et al., 2018; Sala et al., 2018) V1.00 characterization factors with the EF 3.1 normalization and weighting method (Andreasi Bassi et al., 2023). The following impact categories were evaluated:

- Acidification (A, expressed as mol H<sup>+</sup> eq.);
- Climate change (CC, expressed as mass of CO<sub>2</sub> eq.);
- Ecotoxicity, freshwater (FEx expressed as CTUe);
- Particulate matter (PM expressed as disease inc.);
- Eutrophication, marine (ME expressed as mass of N eq.);
- Eutrophication, freshwater (FE expressed as mass of P eq.);
- Eutrophication, terrestrial (TE expressed as mol N eq.);

- Ozone depletion (OD, expressed as mass of CFC-11 eq.);
- Photochemical ozone formation (POF, expressed as mass of NMVOC eq.);
- Resource use, fossils (FRU, expressed as MJ);
- Resource use, minerals and metals (MMRU, expressed as mass of Sb eq.);

## 3. Results

### 3.1. Absolute environmental results

The absolute environmental results for the impact categories evaluated in the two scenarios (CS and AS) are reported in Tables 3–5. Table 3 presents the results for the functional unit (FU) of 1 tonne of maize grain, Table 4 for 1 tonne of high-moisture corn (HMC), and Table 5 for 1 tonne of fresh chopped maize.

The results obtained for maize grain (Table 3, farms 1, 4, and 7) indicate that, for 12 impact categories out of 13 considered, the alternative scenario (AS) shows better environmental results (impact reduction between 2% and 50%) in all farms. This improvement is related to the lower application of mineral fertilizers and to the use of nitrification inhibitor and biostimulant. In farm 4, marine eutrophication shows a higher impact (+19%) in AS respect to CS because, despite a lower urea dose (from 150 kg/ha in the CS to 50 kg/ha in AS), there is a higher nitrogen leaching related to the application of the biostimulant. In fact, the combined use of the biostimulant and the nitrification inhibitor increases the availability of nitrogen in the soil beyond the plant's absorption capacity: the biostimulant (composed of endophytic bacteria - *Methylobacterium symbioticum* SB23) promotes nitrogen fixation in plant tissues in a form that is easily absorbed by the crop, while the inhibitor limits nitrogen losses through denitrification. Consequently, although AS reduces the use of mineral and organic fertilizers and leads to higher yields in most farms, it can still cause an increase in nitrogen leaching under specific soil or management conditions, especially if fertilization is not sufficiently reduced.

For the functional unit of 1 tonne of high-moisture corn (Table 4), the comparison between CS and AS on farm 2 and farm 9 shows improvements in 10 out of the 13 impact categories, with reductions ranging from 1% to 87%. The greatest reduction (87%) is observed for particulate matter (PM) on Farm 9, mainly due to lower ammonia emissions resulting from a decreased application rate of digestate before seeding (from 40 t/ha to 10 t/ha). Conversely, freshwater ecotoxicity, ozone depletion, and photochemical ozone formation show higher impacts in the AS than in the CS. Importantly, despite yield reductions of 2% and 7% under the alternative management, most environmental impacts decrease. This offsetting effect is mainly attributed to the reduction in nitrous oxide and ammonia emissions, which compensates for the impact increase related to the lower yield. The increases observed for freshwater ecotoxicity (+1% and +9%) are linked to the use of the nitrification inhibitor, while the higher ozone depletion (+6%) and photochemical ozone formation (+4%) are due to the additional self-propelled sprayer pass required for the biostimulant application.

For fresh chopped maize (Table 5), the comparison between the CS and AS across the nine farms shows improvements in 12 out of the 13 impact categories, with reductions ranging from 1% to 83%. The largest reduction (83%) is observed in the ozone depletion (OD) category on Farm 8, mainly due to a lower use of mineral fertilizers, particularly urea applied to cover crops, whose application decreased from 0.60 t/ha to 0.26 t/ha. This reduction led to a proportional decrease in nitrous oxide emissions.

In contrast, marine eutrophication showed higher impacts under the AS in Farms 5 and 6 (+82% and +66%, respectively). In both cases, this increase was related to the maintenance of similar mineral fertilizer rates between the two scenarios, combined with the additional application of the biostimulant, which enhanced nitrogen leaching and consequently increased the impact in the marine eutrophication

**Table 3**  
Absolute results for 1 ton of maize grain and impact variation (Δ%) in the Alternative Scenario.

Impact Categories	Unit	FARM 1 - 2023		FARM 4 - 2023		FARM 7 - 2023	
		CS	Δ	CS	Δ	CS	Δ
Acidification	mol H+ eq	17.03	-48%	3.80	-47%	19.79	-42%
Climate change	kg CO <sub>2</sub> eq	332.00	-50%	159.58	-19%	494.87	-42%
Ecotoxicity, freshwater	CTUe	2415.25	-17%	200637.19	-2%	5550.50	-9%
Particulate matter	disease inc./10 <sup>6</sup>	118.44	-48%	25.54	-49%	137.38	-43%
Eutrophication, marine	kg N eq	13.06	-46%	3.09	19%	25.48	-26%
Eutrophication, freshwater	kg P eq	0.05	-13%	0.11	-3%	0.13	-6%
Eutrophication, terrestrial	mol N eq	75.12	-48%	16.75	-47%	86.65	-43%
Ozone depletion	mg CFC11 eq	9.65	-17%	5.14	-6%	13.19	-15%
Photochemical ozone formation	kg NMVOC eq	0.86	-16%	0.50	-5%	1.26	-13%
Resource use, fossils	MJ	2728.18	-34%	930.74	-21%	4118.08	-24%
Res. use, minerals and metals	g Sb eq	1.65	-25%	0.52	-17%	2.37	-19%

$$\Delta = \text{impact variation (\%)} \text{ from CS and AS calculated as: } \left( \frac{\text{Absolute result AS}}{\text{Absolute result CS}} - 1 \right) \cdot 100.$$

**Table 4**  
Absolute results for 1 ton of high-moisture corn and impact variation (Δ%) in the Alternative Scenario.

Impact Categories	Unit	FARM 2 - 2023		FARM 9 - 2024	
		CS	Δ	CS	Δ
Acidification	mol H+ eq	11.14	-26%	8.18	-84%
Climate change	kg CO <sub>2</sub> eq	116.77	-59%	96.91	-15%
Ecotoxicity, freshwater	CTUe	17586.66	1%	110.79	9%
Particulate matter	disease inc./10 <sup>6</sup>	77.45	-27%	55.26	-87%
Eutrophication, marine	kg N eq	3.47	-72%	2.11	-21%
Eutrophication, freshwater	kg P eq	0.03	-7%	0.03	-35%
Eutrophication, terrestrial	mol N eq	49.48	-26%	36.33	-84%
Ozone depletion	mg CFC11 eq	4.13	-15%	6.43	6%
Photochemical ozone formation	kg NMVOC eq	0.29	-18%	0.65	4%
Resource use, fossils	MJ	715.89	-49%	932.49	-2%
Res. use, minerals and metals	g Sb eq	0.45	-35%	0.65	-5%

$$\Delta = \text{impact variation (\%)} \text{ from CS and AS calculated as: } \left( \frac{\text{Absolute result AS}}{\text{Absolute result CS}} - 1 \right) \cdot 100.$$

category, without sufficiently reducing mineral fertilization.

### 3.2. Contribution analysis

The results of the contribution analysis are reported in Table 6 for the maize grain FU, while in the supplementary materials (Table S16 and S17) for the other two FU. However, the results show a rather similar trend in all farms and for all FUs considered. In particular, the contribution analysis highlighted two main aspects:

- In both the conventional (CS) and alternative (AS) scenarios, ammonia emissions represented the main hotspot for acidification, particulate matter, and terrestrial eutrophication, accounting for more than 95 % of the total impact in each case. This outcome confirms the central role of ammonia volatilization from organic fertilizer application, particularly digestate spreading before seeding, as a key driver of these categories. In contrast, nitrous oxide (N<sub>2</sub>O) emissions were the dominant source of climate change impacts (40–55 %), while nitrate leaching contributed almost entirely to marine eutrophication (>85 %), and phosphate emissions to freshwater eutrophication (>75 %). Pesticide emissions were almost exclusively responsible for freshwater ecotoxicity (>85 %).

- Mechanization and production factors were instead the main contributors to ozone depletion, photochemical ozone formation, and resource use (fossils and minerals/metals), with combined contributions exceeding 60–80 %. In the AS, the relative share of mechanization increased slightly due to the additional field pass required for the distribution of the biostimulant, although this effect remained marginal in absolute terms. Conversely, the use of the nitrification inhibitor led to a systematic reduction in the contribution of N<sub>2</sub>O emissions to climate change, while the partial substitution of mineral fertilizer with the biostimulant reduced impacts associated with fertilizer production within the “production factors” group.

Overall, the relative contribution was consistent across the three functional units (grain, high-moisture corn, and fresh chopped maize), confirming that the main environmental hotspots of maize cultivation are primarily linked to nitrogen-related field emissions, followed by mechanization and production factors, whereas the contribution of the two products (biostimulant and nitrification inhibitor) remained negligible (<1 % across all categories).

### 3.3. Sensitivity analysis and uncertainty analysis

The outcomes of LCA studies are influenced by methodological decisions and underlying assumptions (such as those related to emission modelling). To assess how these choices, along with model uncertainty and data variability, impact the environmental results, both sensitivity and uncertainty analyses were conducted. Specifically, a sensitivity analysis was performed to examine the influence of key modelling choices on the environmental outcomes. In particular, the Life Cycle Impact Assessment (LCIA) method was applied to characterize the inventory data. In this context, alongside the EF 3.1 method, ReCiPe 2016 Midpoint (H) V1.08/World (2010) H method was also taken into consideration. The ReCiPe method was originally developed in 2008 and was updated to its current version in 2016 (Huijbregts et al., 2017). Owing to its inclusion of global characterization factors, ReCiPe is among the most widely used and versatile methods for impact assessment.

In addition, a dedicated sensitivity analysis was performed to assess the influence of the assumed nitrogen-equivalent contribution of the biostimulant as reported in section 2.4.

#### 3.3.1. ReCiPe midpoint (H)

A direct comparison of the environmental outcomes derived from the two LCIA methods is not feasible for all impact categories, as they employ different indicators and units of measurement. Nevertheless, the overall comparison reveals consistent trends across both methods. More specifically, each LCIA approach yields distinct results that are useful for identifying the most and least favorable scenarios.

**Table 5**  
Absolute results for 1 ton of fresh chopped maize and impact variation ( $\Delta$ ) in the Alternative Scenario.

Impact Categories <sup>a</sup>	Unit	FARM 3 - 2023		FARM 5 - 2023		FARM 6 - 2023		FARM 8 - 2024		FARM 10 - 2024		FARM 11 - 2024		FARM 12 - 2024		FARM 13 - 2024		FARM 14 - 2024	
		CS	$\Delta$	CS	$\Delta$	CS	$\Delta$	CS	$\Delta$	CS	$\Delta$	CS	$\Delta$	CS	$\Delta$	CS	$\Delta$	CS	$\Delta$
A	mol H <sub>2</sub> O eq	1.74	-40%	6.86	-17%	8.87	-9%	4.41	-56%	2.17	-40%	3.63	-35%	3.63	-48%	2.80	-21%	5.32	-32%
CC	kg CO <sub>2</sub> eq	58.91	-43%	53.91	-29%	41.59	-24%	119.46	-56%	60.91	-40%	80.63	-22%	80.63	-28%	85.92	-34%	186.16	-36%
FE <sub>X</sub>	CTue	530.24	-9%	464.66	-16%	55277.33	-9%	260.19	-16%	40.73	4%	686.64	-6%	686.64	-7%	439.61	0%	2738.03	-1%
PM	disease inc./10 <sup>6</sup>	11.87	-41%	46.76	-17%	61.32	-9%	29.63	-55%	14.78	-41%	24.69	-36%	24.69	-49%	19.06	-21%	36.20	-33%
ME	kg N eq	1.70	-38%	0.77	82%	0.61	66%	6.32	-36%	2.66	-15%	5.31	-18%	5.31	-17%	5.46	3%	14.63	-3%
FE	kg P eq	0.02	-6%	0.03	-16%	0.04	-9%	0.03	-42%	0.02	-1%	0.03	-8%	0.03	-8%	0.03	-2%	0.06	-3%
TE	mol N eq	7.56	-41%	30.58	-17%	39.53	-9%	19.47	-56%	9.41	-41%	15.85	-36%	15.85	-49%	12.37	-21%	23.42	-32%
OD	mg CFC11 eq	1.25	-8%	3.79	-8%	1.31	-7%	5.12	-83%	0.79	-22%	3.97	-12%	3.97	-15%	1.03	-11%	2.51	-15%
POF	kg NMVOC eq	0.14	-8%	0.34	-11%	0.15	-9%	0.49	-63%	0.15	-8%	0.32	-11%	0.32	-24%	0.24	-4%	0.50	-6%
RUF	MJ	358.51	-22%	444.27	-12%	231.15	-8%	907.47	-50%	416.51	-22%	916.78	-19%	916.78	-27%	546.43	-12%	1235.94	-16%
RUMM	g Sb eq	0.17	-20%	0.23	-10%	0.11	-8%	0.56	-66%	0.15	-29%	0.42	-19%	0.42	-16%	0.16	-18%	0.42	-21%

$\Delta$  = impact variation (%) from CS and AS calculated as:  $\left( \frac{\text{Absolute result AS}}{\text{Absolute result CS}} - 1 \right) \cdot 100$ .

<sup>a</sup> A: Acidification; CC: Climate change; FE<sub>X</sub>: Ecotoxicity, freshwater; ME: Eutrophication, marine; FE: Eutrophication, freshwater; TE: Eutrophication, terrestrial; OD: Ozone depletion; POF: Photochemical ozone formation; FRU: Resource use, fossils; MMRU: Resource use, minerals and metals.

### 3.3.2. Sensitivity analysis on the nitrogen-equivalent contribution of the biostimulant

A sensitivity analysis was conducted to evaluate the effect of the assumed nitrogen-equivalent contribution of the biostimulant on the environmental results. In particular, the baseline value of 50 kg N ha<sup>-1</sup> (AS) was compared with a lower value of 37 kg N ha<sup>-1</sup> (AS1), derived as the average of the 36–38 kg N ha<sup>-1</sup> increase in crop N uptake reported by [Quemada et al. \(2026\)](#) for the same biostimulant. For the sensitivity analysis, crop yields were kept consistent with those considered in the AS scenario.

The analysis showed that this assumption affected only the marine eutrophication impact category, with no significant variations observed in the other impact categories. The observed changes are directly related to the lower amount of nitrogen assumed to be fixed by the biostimulant, which influences only the share of nitrogen lost through leaching, the main driver of marine eutrophication.

When comparing the conventional scenario (CS) with AS1, the number of farms showing an improvement in marine eutrophication decreased from four (AS) to two, reflecting a lower reduction in nitrogen leaching under the AS1 assumption.

Overall, the variation between the two alternative scenarios (AS vs. AS1) ranged from -4% to -39% across the 14 farms. In all cases, AS1 showed lower impacts compared to AS, while maintaining the same trend relative to the conventional scenario.

Detailed results of the sensitivity analysis are reported in [Table S21](#) in the Supplementary Materials.

### 3.3.3. Uncertainty analysis

An uncertainty analysis was performed on the 14 farms considered using the Monte Carlo technique (1000 iterations and a 95% confidence interval) to verify the robustness of the results.

The results confirm that in the alternative scenario (AS) there is a reduction in impacts compared to the conventional scenario (CS) for categories related to nitrogen: climate change (via N<sub>2</sub>O), acidification and particulate matter (via NH<sub>3</sub>) and terrestrial eutrophication (via NH<sub>3</sub>/NO<sub>x</sub>), with narrow uncertainty intervals. Marine eutrophication shows wider uncertainty ranges, in line with site-dependent nitrate leaching responses, where fertilizer rates were kept similar and the biostimulant increased soil nitrogen availability (e.g., farms 5-6). These behaviours are consistent with the contribution analysis, which attributes over 85% of marine eutrophication to nitrate leaching and over 95% of acidification/particulate matter/eutrophication to ammonia volatilization, i.e. the elements included in Brentrup's nitrogen budget model and field fertilization management, which varies from farm to farm (timing/incorporation, temperature, precipitation).

Uncertainty is most pronounced in the category relating to toxicity. The highest levels of uncertainty are found in freshwater ecotoxicity, which stem from the high variability of the characterization factors of pesticide active substances and their emissions, as also reflected in the contribution analysis, where pesticide emissions dominate freshwater ecotoxicity (>85%). In contrast, categories dominated by production factors and mechanization (e.g., resource use, ozone depletion) tend to show relatively narrower uncertainty levels (always <2%) and more pronounced AS improvements when mineral fertilizer production and field passes are reduced (see [supplementary Figures S22-S35](#)). Overall, the results confirm that AS offers robust improvements (with no or only marginal overlaps) in most nitrogen-related impact categories for most farms, while emphasizing that toxicity results remain sensitive to the uncertainty of pesticide characterization factors.

## 4. Discussion

The growing interest in biostimulants and nitrification inhibitors is driven by the need to increase crop productivity while mitigating the negative environmental impacts of mineral fertilizers. In this study, we evaluated the agronomic performance of microbial-based biostimulants

**Table 6**

Contribution analysis results for Farm 2 (FU 1 ton of maize grain): relative impact share (%) of individual inputs to the total impact.

Contributor	Scenario	A	CC	FEx	PM	ME	FE	TE	OD	POF	RUF	RUMM
Mechanization	CS	1.6	19.0	0.6	1.0	2.3	11.0	1.5	69.6	71.8	36.6	49.6
	AS	2.2	46.8	0.6	1.4	8.5	12.1	2.0	83.7	89.5	72.6	77.0
Production factors	CS	0.9	27.5	6.8	1.4	0.5	12.5	0.5	30.4	28.2	63.4	50.4
	AS	0.3	11.8	6.7	0.8	0.6	4.1	0.2	16.3	10.5	27.4	23.0
Ammonia emissions	CS	97.6	0.0	2.8	97.6	9.5	0.0	98.0	0.0	0.0	0.0	0.0
	AS	97.5	0.0	2.0	97.9	25.0	0.0	97.8	0.0	0.0	0.0	0.0
Dinitrogen monoxide emissions	CS	0.0	53.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	AS	0.0	38.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nitrate emissions	CS	0.0	0.0	0.0	0.0	87.6	0.0	0.0	0.0	0.0	0.0	0.0
	AS	0.0	0.0	0.0	0.0	65.9	0.0	0.0	0.0	0.0	0.0	0.0
Phosphate emissions	CS	0.0	0.0	0.0	0.0	0.0	76.5	0.0	0.0	0.0	0.0	0.0
	AS	0.0	0.0	0.0	0.0	0.0	83.8	0.0	0.0	0.0	0.0	0.0
Pesticide emissions	CS	0.0	0.0	89.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	AS	0.0	2.6	90.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

A: Acidification; CC: Climate change; FEx: Ecotoxicity, freshwater; PM: Particulate matter; ME: Eutrophication, marine; FE: Eutrophication, freshwater; TE: Eutrophication, terrestrial; OD: Ozone depletion; POF: Photochemical ozone formation; FRU: Resource use, fossils; MMRU: Resource use, minerals and metals.

(*Methylobacterium symbioticum* SB23), and nitrification inhibitor (nitrapyrin-based), within the framework of sustainable maize production. These findings should be interpreted considering the environmental results obtained in this study, where differences between scenarios were mainly driven by changes in nitrogen dynamics and associated emissions.

Field results from [Gajula et al. \(2025\)](#) demonstrated that nitrogen rates positively affected grain yield at all three site-years, whereas biostimulants effects on grain yield were only observed at one site (Stoneville 2022). Moreover, the synergy between biostimulants and nitrogen rates was minimal, suggesting that product efficacy is context-dependent and potentially constrained by soil, climatic, or microbial competition factors.

Nitrogen mineral fertilizers characterized by slow-release mechanisms and some microbial interactions, still under study, evidenced a limited yield response, as reported by [Quemada et al. \(2019\)](#), particularly when stabilized with inhibitors such as nitrapyrin. These nitrification inhibitors slow the conversion of ammonium to nitrate, reducing nitrogen losses via leaching and denitrification, and increasing nitrogen retention in the soil. While their immediate agronomic benefit is established, their long-term effects on microbial communities and subsequent crop cycles are still under investigation. This mechanism directly influences environmental impact categories such as climate change and marine eutrophication, as reduced nitrification can lower N<sub>2</sub>O emissions while potentially affecting nitrate leaching patterns.

Despite modest field-level performance, biostimulants offer notable potential from a sustainability perspective. [Calia et al. \(2025\)](#) conducted a life cycle assessment (LCA) of *Trichoderma*-based microbial biostimulants and identified key environmental hotspots in the production process. These findings emphasize the dual value of biostimulants: not only as inputs for improved nutrient use efficiency and stress tolerance, but also as eco-friendly products whose production processes can be optimized for minimal environmental impact.

In the context of integrated nitrogen management, products like the nitrification inhibitor complement biostimulants by stabilizing ammonium nitrogen in soils, thereby improving the temporal availability of nitrogen and reducing environmental losses. When used together, microbial biostimulants and nitrification inhibitors may offer additive or synergistic effects on nitrogen use efficiency, especially under low to moderate fertilization regimes. However, more research is needed to understand optimal dosage, timing, application methods, and interactions with specific soil microbiomes and crop genotypes.

The results highlight the presence of environmental trade-offs associated with improved nitrogen management strategies. While the use of biostimulants and nitrification inhibitors can reduce certain impacts, particularly those related to gaseous emissions (e.g., climate change), they may also influence other pathways, such as nitrate leaching,

increasing impacts in categories such as marine eutrophication. The reduction in climate change impacts observed in this study is consistent with previous findings showing that nitrification inhibitors can significantly decrease N<sub>2</sub>O emissions from agricultural soils ([Akiyama et al., 2010](#)).

The increase observed in marine eutrophication in some cases can be attributed to higher nitrate leaching, likely resulting from an imbalance between nitrogen supply and crop uptake. While the use of biostimulants may reduce mineral fertilizer inputs, an improper recalibration of fertilization practices can lead to excess nitrogen availability in the soil, thereby enhancing nitrate losses to water bodies. Similarly, the influence of nitrogen fertilization on environmental impacts observed in this study is in line with [Brentrup et al. \(2004\)](#). This highlights the importance of adjusting nitrogen management strategies to site-specific conditions, including soil properties and crop requirements, in order to avoid unintended environmental trade-offs.

These findings are consistent with recent field experiments showing that *Methylobacterium symbioticum* can enhance crop N uptake and yield under low nitrogen conditions, although its effect tends to diminish when mineral N is sufficiently available ([Quemada et al., 2026](#)).

The uncertainty analysis further supports the robustness of the results. In particular, the Monte Carlo simulation showed limited overlap between the conventional and alternative scenarios for nitrogen-related impact categories (e.g., climate change, acidification, and terrestrial eutrophication), confirming the consistency of the observed reductions.

Conversely, wider uncertainty ranges were observed for categories such as marine eutrophication and freshwater ecotoxicity, reflecting the high variability associated with site-specific conditions (e.g., nitrate leaching) and characterization factors (e.g., pesticide emissions). These results highlight that, while the overall environmental benefits of the alternative scenario are robust, some impact categories remain sensitive to local conditions and modelling assumptions.

The comparison of performance with other recently published studies on crop cultivation ([Boone et al., 2016](#); [Supasri et al., 2020](#)), including maize cultivation for grain ([Bacenetti et al., 2016](#); [Gaglio et al., 2019](#)) and fresh chopped maize ([Bacenetti and Fusi, 2015](#); [Noya et al., 2018](#); [Vigo et al., 2025](#)), revealed a strong similarity with the results of this study, particularly regarding mechanization, production factors in conventional scenarios, and emissions from fertilizer and pesticide.

Current literature suggests that biostimulant efficacy is highly variable and influenced by multiple biotic and abiotic factors. This variability is reflected in the present study, where differences among scenarios were strongly influenced by site-specific conditions, particularly soil characteristics and nitrogen availability. This highlights the need for more robust, multi-environment field trials, standardization of

product formulations, and clarification of regulatory definitions (du Jardin, 2015; Rouphael and Colla, 2020). Moreover, future work should integrate agronomic outcomes with environmental costs of production and transport (e.g., greenhouse gas emissions) to assess the full sustainability profile of these products.

Although this study focuses on environmental performance, economic aspects are also relevant when considering the adoption of these practices. The use of microbial biostimulants and nitrification inhibitors involves additional input costs; however, these may be partially or fully offset by reductions in mineral fertilizer use, particularly in contexts where fertilizer prices are high. This aspect has become particularly relevant in recent years due to the volatility of mineral fertilizer prices. Therefore, the overall economic outcome is expected to depend on the balance between input substitution and productivity effects and is likely to be highly context specific. In conclusion, microbial biostimulants and nitrogen stabilizers represent promising tools for improving nitrogen use efficiency and crop productivity, although their effects are context-specific and may require tailored management strategies. Integrating agronomic performance with environmental life cycle assessments is essential to support their effective implementation in sustainable agriculture. These findings confirm that nitrogen management is a key leverage point for reducing environmental impacts in maize cultivation, while highlighting the importance of considering trade-offs.

A limitation of this study is the relatively small and unevenly distributed sample size across different production types. However, the dataset is based on real farm data and reflects the variability of current agricultural practices. Future studies including a larger and more balanced dataset would help to strengthen the robustness of the results.

## 5. Conclusions

The analysis conducted shows a complex picture of the environmental impacts associated with the use of a biostimulant and nitrification inhibitor in maize cultivation, highlighting how the adoption of sustainable agronomic practices is an effective strategy for reducing the overall environmental footprint in numerous impact categories.

Sustainable farming techniques, characterized by a significant reduction in the use of mineral fertilizers and the introduction of innovative products such as the nitrification inhibitor and the biostimulant, have contributed to a marked reduction in impacts in key categories such as climate change, acidification, particulate matter and ozone depletion. In many farms, these decreases reached significant values, with reductions of up to 87% for some categories.

By reducing dinitrogen monoxide emissions, the use of nitrification inhibitor has a positive effect on climate change. In parallel, the application of biostimulant has resulted in a reduction in the use of mineral fertilizers. However, in some cases, the use of biostimulant has resulted in increased impacts related to marine eutrophication due to increased nitrate leaching. In such cases, mineral and organic fertilization should be carefully recalibrated considering the input of the biostimulant.

Agricultural mechanization, while representing a substantial contribution to impacts in categories such as climate change and acidification, did not vary significantly between the two scenarios.

Overall, the impact related to the two products that characterize sustainable management, although modeled based on a simplified inventory, is modest, negligible in the case of some environmental impacts.

The sustainable approach demonstrated greater environmental efficiency, contributing to an average reduction in impacts in the farms analyzed, without affecting yields in most of the contexts analyzed. However, these findings should be interpreted with caution due to the variability among farms and the context-specific nature of the results. These results, while deserving verification over at least a three-year time frame to better assess the effect of soil and climate conditions, underscore the importance of adopting innovative and sustainable farming practices to reduce the environmental footprint of agriculture while

maintaining or improving productivity. In practical terms, these results suggest that optimizing nitrogen inputs through the combined use of biostimulants and nitrification inhibitors can support more efficient and sustainable fertilization strategies at the farm level. The emerging evidence reinforces the urgency of promoting a transition to agronomic models that combine sustainability and economic competitiveness.

Future studies should test these findings under different environmental conditions beyond the temperate Italian context, to verify the robustness of results across diverse soils and climates. In addition, the two tested products should be evaluated when applied before sowing or crop emergence and extended to other crop types such as autumn–winter cereals (barley, wheat, triticale) and summer crops like sorghum. Such trials would help to better understand the effectiveness and environmental performance of these solutions under a wider range of agronomic conditions. Moreover, further studies integrating agronomic performance with environmental and economic assessments are needed to evaluate the overall sustainability of these technologies under real farming conditions. In particular, long-term field experiments are required to assess the stability of biostimulant effects across different years and environmental conditions, considering the strong influence of climatic variability on crop productivity. Additional research should also focus on optimizing the combination and dosage of biostimulants and nitrification inhibitors under different soil types and fertilization regimes, as their effectiveness can vary depending on interactions with soil properties and nitrogen dynamics (Xiao et al., 2023). Furthermore, several studies have highlighted that biostimulants can enhance nutrient use efficiency and plant tolerance to abiotic stress, although their mechanisms of action and field-scale performance remain only partially understood (Trevisan et al., 2019). Future research should also aim to improve the environmental modelling of these products, particularly in LCA studies, by incorporating more detailed inventory data for biostimulant production processes and reducing current uncertainties associated with proxy datasets. In addition, expanding experimental trials across different agro-climatic regions is essential to verify the transferability of results, as crop responses to climate variability and management practices are highly context-dependent. Finally, a better understanding of the interactions between soil properties, crop response, and nitrogen dynamics would support the development of more precise and site-specific fertilization strategies, contributing to both improved productivity and reduced environmental impacts.

## CRedit authorship contribution statement

**Filippo Vigo:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft. **Michele Zoli:** Data curation, Supervision, Validation, Writing – review & editing. **Jessica Murelli:** Data curation, Investigation, Validation, Writing – review & editing. **Jacopo Bacenetti:** Data curation, Software, Supervision, Validation, Writing – review & editing.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Prof. Jacopo Bacenetti reports financial support was provided by Pioneer Hi-Bred Italia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2026.148606>.

## Data availability

The data that has been used is confidential.

## References

- Ahmad, A., Zoli, M., Latella, C., Bacenetti, J., 2023. Rice cultivation and processing: highlights from a life cycle thinking perspective. *Sci. Total Environ.* 871, 162079.
- Akiyama, H., Yan, X., Yagi, K., 2010. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N<sub>2</sub>O and NO emissions from agricultural soils: meta-analysis. *Glob. Change Biol.* 16, 1837–1846. <https://doi.org/10.1111/j.1365-2486.2009.02031.x>.
- Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S., Ardenne, F., 2023. Updated Characterization and Normalisation Factors for the Environmental Footprint 3.1 Method. Publications Office of the European Union, Luxembourg.
- Bacenetti, J., Lovarelli, D., Fiala, M., 2016. Mechanization of organic fertilizer spreading, choice of fertilizer and crop residue management as solutions for maize environmental impact mitigation. *Eur. J. Agron.* 79, 107–118. <https://doi.org/10.1016/j.eja.2016.05.015>.
- Bacenetti, J., Fusi, A., 2015. The environmental burdens of maize silage production: influence of different ensiling techniques. *Anim. Feed Sci. Technol.* 204, 88–98.
- Bahmutsky, S., Grassauer, F., Arulnathan, V., Pelletier, N., 2024. A review of life cycle impacts and costs of precision agriculture for cultivation of field crops. *Sustain. Prod. Consum.* 52, 347–362. <https://doi.org/10.1016/j.spc.2024.11.010>.
- Boone, L., De Meester, S., Vandecasteele, B., Muylle, H., Roldán-Ruiz, I., Nemeček, T., Dewulf, J., 2016. Environmental life cycle assessment of grain maize production: an analysis of factors causing variability. *Sci. Total Environ.* 553, 551–564. <https://doi.org/10.1016/j.scitotenv.2016.02.089>.
- Bouhzam, I., Azarkamand, S., Puig, R., Bala, A., Fullana-i-Palmer, P., Szadovskii, I., et al., 2025. Assessing environmental impacts of various biofertilizers in Europe: a step toward circular economy transition. *Sustain. Prod. Consum.* <https://doi.org/10.1016/j.spc.2025.04.012>.
- Brentrup, F., Küsters, J., Lammel, J., Barraclough, P., Kuhlmann, H., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer use in winter wheat production systems. *Eur. J. Agron.*
- Brentrup, F., Küsters, J., Lammel, J., Kuhlmann, H., 2000. Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. *Int. J. Life Cycle Assess.* 5, 349–357.
- Calia, Claudio, García, Sara González, Ingraio, Carlo, Lagioia, Giovanni, Ruta, Claudia, Secchi, Nicola, Mastro, Giuseppe De, 2025. Life cycle assessment of microbial plant biostimulant production for application in sustainable agricultural systems. *Sci. Total Environ.* 981.
- Cheng, Z., Wang, F., Wang, Z., Wang, Y., Rong, M., Wang, T., Wang, Z., 2025. Strip-till farming: combining controlled-release blended fertilizer to enhance Rainfed maize N use efficiency while mitigate N<sub>2</sub>O footprint and carbon footprint in the hilly region of Northeast China. *J. Agric. Food Res.* 102313
- Corteve Agriscience, 2023a. BlueN technical sheet. <https://www.corteve.it>.
- Corteve Agriscience, 2023b. Instinct technical information. <https://www.corteve.it>.
- Costantini, M., Zoli, M., Ceruti, M., Crudele, R., Guarino, M., Bacenetti, J., 2023. Environmental effect of improved forage fertilization practices in the beef production chain. *Sci. Total Environ.* 902.
- David, C., Amaro, X., Rosentrater, K.A., Ghnimi, S., 2025. Comparative life cycle assessment of perennial and annual crop production: impact of farming systems and management practices. *Front. Sustain. Food Syst.* 9, 1569398.
- Dell, C.J., Meisinger, J.J., Beegle, D.B., 2020. Nitrogen retention and corn yield in response to nitrpyrin inhibitor and application method. *Agron. J.* 112 (3), 2349–2359.
- Detzel, A., Krüger, M., Busch, M., Blanco-Gutiérrez, I., Varela, C., Manners, R., Zannini, E., 2022. Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: an environmental perspective. *J. Sci. Food Agric.* 102 (12), 5098–5110.
- European Commission, 2020. Farm to Fork Strategy.
- Fallahpour, F., Aminghafouri, A., Ghalegolab Behbahani, A., Bannayan, M., 2012. The environmental impact assessment of wheat and barley production by using life cycle assessment (LCA) methodology. *Environ. Dev. Sustain.* 14 (6), 979–992.
- Fazio, S., Biganzoli, F., De Laurentiis, V., Zampori, L., Sala, S., Diaconu, E., 2018. Supporting Information to the Characterization Factors of Recommended EF Life Cycle Impact Assessment Methods. EUR 29600 EN, Publications Office of the European Union, Luxembourg, 978-92-79-98585-0.
- Gaglio, M., Tamburini, E., Lucchesi, F., Aschonitis, V., Atti, A., Castaldelli, G., Fano, E.A., 2019. Life cycle assessment of maize-germ oil production and the use of biogeno to mitigate environmental impacts: a gate-to-gate case study. *Resources* 8 (2), 60. <https://doi.org/10.3390/resources8020060>.
- Gajula, P., Dhillon, J., Sharma, R.K., Bryant, C., Bheemanahalli, R., Reed, V., Larson, E., 2025. Evaluating the impact of biostimulants at variable nitrogen rates in corn production. *Eur. J. Agron.* 167.
- Giongo, V., da Silva Acosta, A., Dossa, Á.A., Santi, A., do Amaral, A.J., Caierao, E., da Silva Santana, M., 2025. How can the environmental impacts of wheat cultivation and wheat flour production be reduced? A life cycle assessment of Brazilian wheat. *J. Clean. Prod.* 489, 144650.
- Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* 22, 138–147. <https://doi.org/10.1007/s11367-016-1246-y>.
- ISMEA, 2023. Sustainability and Innovation in Agriculture: Trends and Scenarios.
- ISO 14040, 2006a. Environmental Management — Life Cycle Assessment — Principles and Framework. International Organization for Standardization.
- ISO 14040, 2006b. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization.
- Koch, P., Salou, T., 2022. AGRIBALYSE® : Rapport Méthodologique- Volet Agricultureversion 3.1 ; Version Initiale v1.0, 2014. ADEME, Angers, France, p. 342.
- Losada, R.L., Larsson, C., Brady, M.V., Wilhelmsson, F., Hedlund, K., 2025. Advancing sustainability transformations in agriculture: an agent-based life cycle assessment for supporting policymaking. *Sustain. Prod. Consum.* <https://doi.org/10.1016/j.spc.2025.09.008>.
- Lovarelli, Daniela, Bacenetti, Jacopo, 2017. Bridging the gap between reliable data collection and the environmental impact for mechanised field operations. *Biosystems Engineering* 160, 109–123. <https://doi.org/10.1016/j.biosystemseng.2017.06.002>. <https://linkinghub.elsevier.com/retrieve/pii/S1537511017303112>.
- Mahmood, A., Ghani, H.U., Gheewala, S.H., 2023. Absolute environmental sustainability assessment of rice in Pakistan using a planetary boundary-based approach. *Sustain. Prod. Consum.* 39, 123–133. <https://doi.org/10.1016/j.spc.2023.05.016>.
- Moreno Ruiz, E., Valsasina, L., FitzGerald, D., Brunner, F., Vadenbo, C., Bauer, C., et al., 2016. Documentation of changes implemented in ecoinvent database v3. 3. Ecoinvent, Zürich, Switzerland.
- Noya, I., Gonzalez-García, S., Bacenetti, J., Fiala, M., Moreira, M.T., 2018. Environmental impacts of the cultivation-phase associated with agricultural crops for feed production. *J. Clean. Prod.* 172, 3721–3733. <https://doi.org/10.1016/j.jclepro.2017.07.132>.
- Noya, I., González-García, S., Bacenetti, J., Arroja, L., Moreira, M.T., 2015. Comparative life cycle assessment of three representative feed cereals production in the Po valley (Italy). *J. Clean. Prod.* 99, 250–265.
- Ocwa, A., Mohammed, S., Mousavi, 2024. Maize grain yield and quality improvement through biostimulant application: a systematic review. *J. Soil Sci. Plant Nutr.* 1609–1649.
- Patrick du Jardin, 2015. Plant biostimulants: definition, concept, main categories and regulation. *Sci. Hortic.* 196, 3–14. <https://doi.org/10.1016/j.scienta.2015.09.021>. ISSN 0304-4238.
- PCR 2020:07 Arable and vegetable crops (1.0.2); Prepared by LCE, Quantis, CCPB, Barilla, LCAlab. CPC name: oilseeds and oleaginous fruits, cereals, pulses (dried leguminous vegetables), forage products, fibres, living plants, cut flowers and flower buds, unmanufactured tobacco, and natural rubber, Vegetables. Valid until: 2025-06-07.
- Quemada, M., Alonso-Ayuso, M., Esteban, R., González, E., 2026. Maize (*Zea mays* L.) response to the biostimulant *Methylobacterium symbioticum* under various nitrogen fertilizer rates. *Eur. J. Agron.* 172.
- Quemada, M., Alonso-Ayuso, María, Hinojosa, Castellano, Antonio, Bedmar, Eulogio, Gabriel, Jose, González, García, Irene, Madrona, Valentín, Francisco, Calvo Alonso, Manuel, 2019. Residual effect of synthetic nitrogen fertilizers and impact on soil nitrifiers. *Eur. J. Agron.* 109, 125917. <https://doi.org/10.1016/j.eja.2019.125917>.
- Rosenbaum, Ralph K., Anton, Assumpció, Bengoa, Xavier, Bjørn, Anders, Brain, Richard, et al., 2015. The Glasgow consensus on the delineation between pesticide emission inventory and impact assessment for LCA. *The International Journal of Life Cycle Assessment* 20 (6), 765–776. <https://doi.org/10.1007/s11367-015-0871-1>. <http://link.springer.com/10.1007/s11367-015-0871-1>. (Accessed 28 March 2015).
- Rouphael, Y., Colla, G., 2020. Biostimulants in agriculture. *Front. Plant Sci.* 11, 40.
- Sala, S., Cerutti, A.K., Pant, R., 2018. Development of a Weighting Approach for the Environmental Footprint. Publications Office of the European Union, Luxembourg, 978-92-79-68041-0.
- Shao, Guodong, Zhou, Jie, Liu, Buchun, Alharbi, Sulaiman Almarai, Liu, Enke, Kuzyakov, Yakov, 2024. Carbon footprint of maize-wheat cropping system after 40-year fertilization. *Sci. Total Environ.* 926.
- Stylianou, M., Papamichael, I., Voukkali, I., Tsangas, M., Omirou, M., Ioannides, I.M., Zorpas, A.A., 2023. LCA of barley production: a case study from Cyprus. *Int. J. Environ. Res. Publ. Health* 20 (3), 2417. <https://doi.org/10.3390/ijerph20032417>.
- Subbarao, G.V., et al., 2006. Evidence for biological nitrification inhibition in *Brachiaria humidicola*: I. Soil and plant studies. *Plant Soil* 282, 281–296.
- Supasri, T., Itsubo, N., Gheewala, S.H., Sampattagul, S., 2020. Life cycle assessment of maize cultivation and biomass utilization in northern Thailand. *Sci. Rep.* 10 (1), 3516. <https://doi.org/10.1038/s41598-020-60532-2>.
- Trevisan, Sara, Manoli, Alessandro, Quaggiotti, Silvia, 2019. A novel biostimulant, belonging to protein hydrolysates, mitigates abiotic stress effects on maize seedlings grown in hydroponics. *Agronomy* 9, 28. <https://doi.org/10.3390/agronomy9010028>.
- Tricase, C., Lamonaca, E., Ingraio, C., Bacenetti, J., Lo Giudice, A., 2018. A comparative life cycle assessment between organic and conventional barley cultivation for sustainable agricultural pathways. *J. Clean. Prod.* 172, 3747–3759. <https://doi.org/10.1016/j.jclepro.2017.07.008>.
- Vatsanidou, A., Konstantinidi, S., Bonos, E., Skoufos, I., 2025. Comparative life cycle assessment of animal feed formulations containing conventional and insect-based protein sources. *AgriEngineering* 7 (9), 275.
- Vigo, F., Zoli, M., Lovarelli, D., Bacenetti, J., 2025. Environmental impact assessment of maize cultivation system considering different irrigation methods. *J. Agric. Eng.* <http://www.agroengineering.org/jae/article/view/1663>.
- Weidema, B.P., Bauer, C., Hischer, R., Mutel, C., Nemeček, T., Reinhard, J., et al., 2013. Overview and methodology: Data quality guideline for the ecoinvent database version 3.

- Xiao, F., Li, D., Zhang, L., Du, Y., Xue, Y., Gong, P., Song, Y., Zhang, K., Zhang, Y., Li, Y., Zhang, J., Cui, Y., 2023. Effect of seaweed extracts from different sources combined with urease and nitrification inhibitors. *Bioresources* 18 (2), 3694–3708.
- Xu, Y., Sheng, J., Zhang, Y., Zhang, L., Kan, Z.R., Sun, G., Zheng, J., 2024. The effect on the carbon footprint of the rice-wheat system of substituting chemical fertilizers by pig manure: the results of a field experiment. *Sustain. Prod. Consum.* 49, 1–11. <https://doi.org/10.1016/j.spc.2024.06.003>.
- Yao, Z., Zhang, W., Wang, X., Lu, M., Zhang, W., Liu, D., Gao, X., Chen, Y., Chen, X., 2022. Environmental impacts, human health, and energy consumption of nitrogen management for maize production in subtropical region. *Environ. Sci. Pollut. Res. Int.*
- Zoli, Michele, Paleari, Livia, Confalonieri, Roberto, Bacenetti, Jacopo, 2021. Setting-up of different water managements as mitigation strategy of the environmental impact of paddy rice. *Science of The Total Environment* 799, 149365. <https://doi.org/10.1016/j.scitotenv.2021.149365>, 149365. <https://linkinghub.elsevier.com/retrieve/pii/S0048969721044387>.
- Zucaro, A., Forte, A., Fagnano, M., Fierro, A., 2014. Life cycle assessment of maize cropping under different fertilization alternatives. *Int. J. Perform. Eng.* 10 (4), 427–436.