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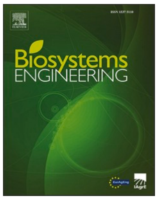

Research Paper

Reducing the environmental impact of maize by fertigation with digestate using pivot and drip systems

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Reducing ammonia emissions is one of the great environmental challenges of the agricultural sector and is by far the most important emitter of this air pollutant. This study analyses maize cultivation with an emerging organic fertilisation management technique, i.e., pre-seeding injection, followed by side-dressing fertigation, through a life cycle assessment approach at the farm gate with the aim of evaluating its influence on crop production as a whole, with a focus on nitrogen emissions during field application. This was done on two sample farms, one of which was fertigated using drip irrigation and the other by pivot irrigation. Each farm was then compared with a reference scenario in which traditional organic fertilisation and irrigation were used. The inventory data consist of measurements made during field trials, data collected from questionnaires to farmers and modelling estimates.

The optimised management of the digestate led to important reductions in the impacts affected by ammonia emissions; acidification was reduced by 68% and 80%. Relevant mitigations were achieved for eutrophication and particulate matter formation and for the carbon footprint (12–14%). A trade-off was identified in the increased impact on the consumption of fossil and mineral resources (13–17%) due to the construction and operation of a vibrating screen operating the filtration of the liquid fraction of digestate. In conclusion, the results indicate the general benefits of improved organic fertilisation management as a whole. Future efforts should be aimed at energy and construction efficiency measures of digestate treatments.

1. Introduction

Ammonia (NH_3) is released into the air (volatilisation) from all ammonium (NH_4^+)-containing products. Ammonia from anthropogenic and natural sources participates in atmospheric reactions (e.g., gas-to-particle conversion), is transported by wind, and returns to the surface through wet and dry deposition processes, leading to adverse effects on the environment and increased public health risks (Ma et al., 2021). The emission and further deposition of ammonia is harmful to ecosystems because it causes acidification and disrupts plant communities. Furthermore, NH_3 is a precursor to the formation of particulate matter, which has adverse effects on human health, affecting the respiratory and cardiovascular systems and causing premature death (De Vries & Melse, 2017). Ammonia is also a precursor of nitrogen oxides and can be, in certain situations, a source of nitrous oxide (N_2O), which is a potent greenhouse gas.

About 94% of European NH_3 emissions stem from agriculture, mainly from the handling of animal manure and the use of fertilisers (EEA, 2016; Sommer et al., 2022). Several studies have estimated that spreading manure accounts for around 24–29% of agricultural emissions (Andersson et al., 2023; Velthof & Mosquera, 2011), although higher rates of ammonia loss can be 30–50% (Hani et al., 2016). This equates to around 790 kt of emissions, a major source of this pollutant (AMEC, 2013).

Therefore, low-emission manure application is the cornerstone of an effective ammonia abatement strategy. Fertigation techniques may contribute significantly at this stage. Some preliminary applications of fertigation were carried out on maize using a dairy slurry by Bortolini (2016) in Italy and by Gamble et al. (2018) in the USA and using digestate in Italy by Mantovi et al. (2020). However, even if the results are promising (Ricco et al., 2021; Ti et al., 2019), it is necessary to approach integrated management considering all potential trade-offs and cascade effects of the practices implemented throughout the whole slurry and manure management system while adopting efficient techniques at every stage.

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Nomenclature

ItemAconym, Unit	
Anaerobic digestion	AD, n/a
Climate change	CC, kg CO_2 eq
Comparative toxic unit for aquatic ecotoxicity impacts	CTUe, n/a
Comparative toxic unit for humans	CTUh, n/a
Freshwater ecotoxicity	FEx, CTUe
Freshwater eutrophication	FE, kg P eq
Functional unit	FU, n/a
Human toxicity with carcinogenic effect	HTc, CTUh
Human toxicity with no carcinogenic effect	HTnc, CTUh
Life cycle assessment	LCA, n/a
Life cycle Inventory	LCI, n/a
Liquid fraction	LF, n/a
Marine eutrophication	ME, kg N eq
Mineral and fossil resource depletion	MFRD, kg Sb eq
Ozone depletion	OD, kg CFC-11 eq
Particulate matter	PM, kg PM2.5 eq
Photochemical ozone formation	POF, kg NMVOC eq
Processing unit	PU, n/a
Soil organic carbon	SOC, kg of SOC•ha^{-1}
Solid fraction	SF, n/a
Terrestrial acidification	TA, molc H+ eq
Terrestrial eutrophication	TE, molc N eq

This study aimed to evaluate the environmental performance of maize cultivation by considering different irrigation and fertigation techniques in Northern Italy using the life cycle assessment (LCA) approach and considering a full set of environmental indicators. Even if originally developed for industrial processes over the years, LCA is increasingly applied for agricultural processes (Notarnicola et al., 2015; Zhang et al., 2018). LCA is based on the analysis of the materials and energy flows characterising the studied production process and, considering different environmental effects, can identify trade-offs among environmental impacts. In addition to the quantification of the environmental performances of the different techniques compared for each of them, the study identifies the subprocesses that mainly contribute to the total impact and discusses possible mitigation solutions. In recent years, several LCA studies have been carried out for crop cultivation (Boone et al., 2016; Fantin et al., 2017; Supasri et al., 2020; Zhang et al., 2018), including maize cultivation for grain (Bacenetti et al., 2015, 2016; Gaglio et al., 2019) and silage (Bacenetti & Fusi, 2015; Noya et al., 2015, 2018). Despite this, to date, no studies have focused on the environmental impact of fertigation technology on maize and other cereal crops.

2. Methods

This study builds on a series of field trials and agronomic monitoring campaigns previously carried out on two farms in Northern Italy in 2019 (Lombardy region, provinces of Cremona and Mantua). In these experiments, maize was grown after winter cereal to produce silage in two consecutive years. The final aim was to compare the use of fertigation techniques using the liquid fraction of digestate after solid separation with traditional irrigation as a reference, focusing on agronomic performance and manure management processes, including N emissions and use efficiency. More details related to the pedoclimatic characteristics of the study area, the agronomic management carried out and the general setting of the monitoring campaigns can be found in Guido et al. (2020). The present work developed a further analysis of the tests carried out by adopting a life cycle perspective, thus using the LCA approach. LCA, defined by two ISO standards (ISO, 2006a; 2006b), is a well-recognised and widely accepted method to quantify the environmental impacts related to products, processes and services. The following paragraphs deal with the development of the assessment, carried out following the four phases envisaged by the reference ISO standards.

2.1. Goal and scope definition

According to ISO standards 14040 and 14044, goal and scope definition is the first step in LCA. In the goal and scope phase, the aims of the study are defined, namely the intended application, the reasons for carrying out the study and the intended audience. The main methodological choices are made in this step, in particular, the exact definition of the functional unit and the identification of the system boundaries.

The goal of this study was to evaluate the environmental impact of maize cultivation by considering different irrigation and fertigation techniques. To this end, maize cultivation trials were carried out in northern Italy. Both provinces are in the Po Valley (latitude: 44° 39’ 46.08" N - longitude: 7° 17’ 46.14" E), one of the most suitable areas in Italy for maize cultivation.

The 4 scenarios combining different irrigation and fertigation techniques were analysed at two different farms (Table 1):

- Farm 1, in Cremona province (45°04′13.2″N–10°07′37.1″E): (i) one reference scenario (RS-P) with a pre-seeding digestate surface distribution carried out using a slurry tank with a splash plate, no side dressing fertilising and irrigation performed using pivot. The pivot was fed using a submerged 23.4 kW pump; (ii) one fertigation scenario (FS–P) with a pre-seeding organic fertiliser distribution carried out using a slurry tank equipped with anchors for digestate injection at a 5–7 cm depth, side dressing fertigation using the liquid fraction of digestate and pivot as the fertigation system.
- Farm 2, in Mantua province (45°03′03.8″N–10°25′53.6″E): (i) one reference scenario (RS-D) with a pre-seeding digestate surface distribution carried out using a slurry tank with splash plate, no side dressing fertilising and irrigation performed using drip irrigation; (ii) one fertigation scenario (FS-D) with injection of digestate before seeding, fertigation with liquid fraction of digestate as side-dressing and drip irrigation system.

The irrigation season at both sites and in both years started in mid-June and ended in August. In farm 1, in RS-P, the pivot covered an

Table 1
Characteristics of the two reference (RSs) and two fertigation (FSs) scenarios.

Scenario	Pre-seeding fertilisation	Side-dressing	Irrigation system	Fertigation	Surface (ha)
RS-P	Digestate surface distribution	Not carried out	Pivot	No	7.0
FS-P	Digestate injection	Liquid fraction digestate/ fertigation	Pivot	Yes	10.6
RS-D	Digestate surface distribution	Not carried out	Drip irrigation	No	9.5
FS-D	Digestate injection	Liquid fraction digestate/ fertigation	Drip irrigation	Yes	19.1

area (270°) of 20.5 ha, 300 m long, with a terminal branch of 20 m, but only 7 ha were monitored for this study, while in FS-P, a central pivot system was established in a semi-circular area (180°) of 10.6 ha, which was 240 m long with a terminal branch of 20 m. In both pivots, the nozzles were positioned every 3 m at a 2.5 m height, and water was sprayed at a pressure of 4 bar. Water was pumped with a mean flow rate of 90 m^3 h^{-1}. Irrigation was generally performed once a week but was adopted according to precipitation events and crop demand; each irrigation event applied 15 mm of water. In farm 2, the monitored area was equipped with drip irrigation systems. In each field, new drip lines were installed at the beginning of the year, positioned every two rows of maize, i.e., every 1.4 m, with drippers placed every 0.5 m under a nominal flow rate of 1.05 L h^{-1} each. The water was pumped at 0.9–1.1 bar pressure in the fields with an average flow rate of 62 m^3 h^{-1}. The water amount applied in each event was 12 mm, on average.

Both the farms have an anaerobic digestion (AD) plant operating in mesophilic conditions and fed with manure, energy crops and by-products. Regarding the management of the digestate, this is not suitable for use directly for fertigation because there is a high risk of clogging the dripper or sprinkler nozzles. For this reason, its treatment was necessary, carried out using highly efficient two-stage solid–liquid separation prototypes designed and installed on farms specifically for this experimentation. The construction materials of the prototypes and the electricity consumed for the treatment were considered for the life cycle inventory. No environmental load was considered for the digestate used because it is a waste of anaerobic digestion.

The general scheme of the separation process was similar for each farm (Fig. 1). The raw digestate (RD) was sent to the first processing unit (PU1) of solid–liquid separation, consisting of a screw press, and the obtained liquid fraction (LF1) was sent to a tank from which it was pumped to the second separator and solid fraction (SF1) that is not used for fertigation. The second separator (processing unit 2 - PU2) consisted of a vibrating screen and the liquid fraction (LF2) was collected in a second tank prior to being injected into the fertigation line. In farm 1, the screw press separator was a Sepcom Horizontal (WAM Italia S.p.A., Ponte Motta/Cavezzo, MO, Italy) with a sieve of 900 μm, and PU2 consisted of a vibrating screen with a sieve of 200 μm. In farm 2, a screw press of 500 μm (sm260 mini—CRI-MAN, Correggio, RE, Italy) and a vibrating screen of 100 μm were used. More details regarding the manufacturing and operation of prototypes can be found in Guido et al. (2020) and Finzi et al. (2021). Lastly, there is a third processing unit (PU3) before the injection of LF2 into the irrigation water.

Regarding the irrigation system, the fertigation scenarios require not only the separator system but also additional pumps with respect to the "irrigation pump" (23.4 and 40.6 kW power in RS-P and RS-D, respectively) that support water distribution using a pivot (in RS-P and FS-P) or drip irrigation system (in RS-D and FS-D). In detail, two additional pumps are operating, one to feed the vibrating screen for the treatment of the liquid fraction (LF1) and one is installed in the vibrating screen and to support fertigation. The total electrical power of these two pumps was 1.86 kW in FS-P and 5.95 kW in FS-D. In both farms, fertigation was carried out between the 8-leaf stage and maize blooming with a distribution of around 130 m^3 ha^{-1} for each event. In farm 1 (pivot), 10 irrigation events were considered. In FS-P, the first 4 events were just with water and the following 6 events had the digestate added. In farm 2 (Drip), 8 fertigation events were considered drip irrigation lines (Typhoon plus by Netafim), which were placed when maize was around the 4-leaf stage.

2.1.1. Functional unit

According to ISO 14040 (ISO, 2006a), the functional unit (FU) of a product system is a quantified description of the performance requirements that the product system fulfils. FU should be measurable, and it is used as a reference unit in an LCA. Although in some cases multiple FUs have been adopted for LCA studies of single crops (e.g., Bernardi et al., 2018; Tricase et al., 2018), mass-based FU is the most widely used for agricultural LCA studies, as it is accepted that the main function of a single crop (at the farm gate) is to deliver a certain quantity of a certain product. In this study, 1 tonne of dry matter of chopped maize biomass was selected as the FU.

2.1.2. System boundary

A "from cradle to farm gate" perspective was adopted. The system boundaries included all operations, from the application of organic fertiliser and soil tillage until harvest and transport of the harvested chopped maize. The following activities were included: raw material extraction (e.g., fossil fuels), manufacture of agricultural inputs (e.g., seed, fertilisers, pesticides and agricultural machines) and energy (e.g., electricity used for the irrigation), use of the agricultural inputs (fertiliser emissions, pesticide emissions, diesel fuel emissions and tire abrasion emissions), maintenance and final disposal of machines, and supply of inputs to the farm. Regarding digestate treatment (Fig. 1), only the operations specifically carried out to produce the liquid fraction used for fertigation were included in the system boundary. Therefore, solid–liquid separation (PU1 in Fig. 1) was not included because it was performed at the biogas plant without fertigation. For the same reason, the management and use of the solid fraction as an organic fertiliser were also excluded from the system boundary.

The downstream processes considered, in addition to the field production per se, were the transport of the harvested chopped biomass to the nearest bunker silo (average distance of 1 km).

Impacts resulting from further transport and processing, distribution, consumption and all related waste disposal were not considered. The impact related to manufacture, maintenance and end-of-life of farm

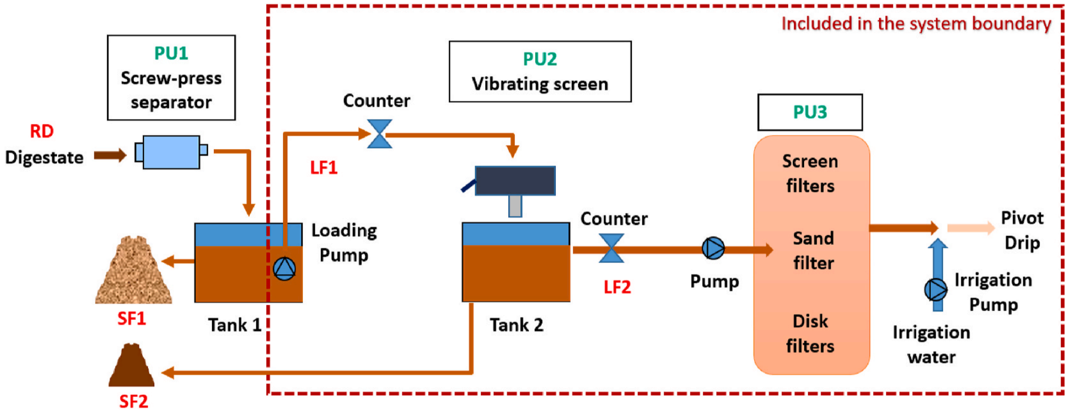

Fig. 1. Scheme of the solid–liquid separation systems on the four farms with the three processing units (two separation units PU1 and PU2 and one filtering unit PU3). (RD = raw digestate; SF = solid fraction; LF = liquid fraction).

infrastructures was excluded. Considering that the goal of this LCA was comparative (i.e., to assess the impact variation due to the different techniques – irrigation vs fertigation), the impacts of the pivot and drip irrigation systems manufacturing were not included due to lack of data. This exclusion slightly affected the absolute results, but because the use of pivot and drip irrigation systems was the same in the reference and fertigation scenarios, it did not influence relative comparisons and the general conclusions.

The demonstration trials were carried out in areas where cereal crops have been grown for many years (>30 years). Consequently, the soil carbon content was supposed to be in equilibrium; therefore, no changes in Soil Organic Carbon (SOC) were considered (Dignac et al., 2017; Han

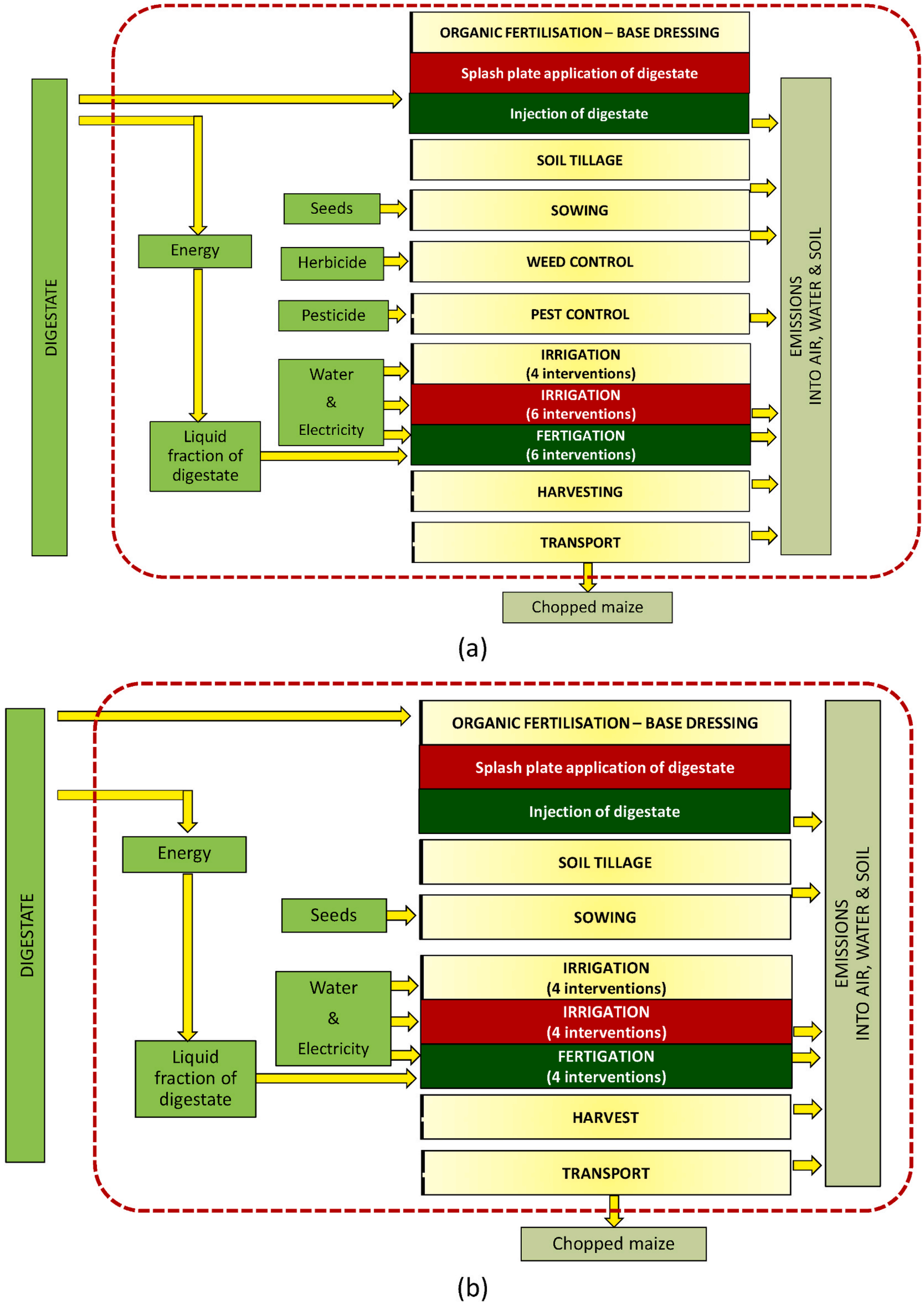

Fig. 2. System boundary for the two cultivation practices (a) for pivot scenarios (RS-P & FS-P) and (b) for drip scenarios (RS-D & FS-D). The inputs/outputs commons in the two scenarios have a light green background; the common operations have a yellow background; those specific for the reference scenario have a red background; and those for the fertigation scenario have a dark green background. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2016).

Since the whole plant is harvested and the crop residues (roots and 30-cm basal portion of the stem) are left in the field and returned to the soil, no co-products are generated. Consequently, no system expansion or allocation is carried out.

Figure 2 shows a general scheme for the system boundaries of the different scenarios.

2.2. *Inventory analysis*

The life cycle inventory (LCI) was built using both primary and secondary data. Primary data were the information directly collected by surveys, field measurement and farmer interviews, while the secondary data were estimated using emission models or were retrieved from literature and/or databases.

Primary data about the cultivation techniques, the sequences of the field operations, and the amount of the different production factors used (e.g., seeds, fuels, fertilisers, pesticides, electricity) were collected during the field trials, while the information about the different machinery (tractors, operative machines and combine harvesters), such as mass, power, working time and working capacity, were retrieved thanks to surveys at the farms.

Primary data were integrated with secondary data derived from estimation models, retrieved from the literature, and concerning on-field pollutant emissions related to field cultivation. Concerning the emissions related to fertilisation, NH_3 volatilisation was measured by passive samplers (CEH ALPHA® samplers) and evaluated with WindTrax 2.0 software, as detailed by Flesch et al. (2004). This process made it possible to estimate ammonia emission factors per hectare and, consequently, emission rates with respect to the applied N. These are reported in Table 2.

The emissions of other N compounds (N_2O, NO_3) were assessed according to Brentrup et al. (2000). This model is based on the N balance between (i) supply coming from the application of fertilisers, N released from crop residue mineralisation, and N atmospheric deposition and (ii) N removal related to the N content in the harvested biomass. NO_3 leaching was assessed considering soil characteristics, rainfall and the N available into the soil after ammonia volatilisation, denitrification and crop removal.

Phosphate emissions were calculated following Prahsun (2006, pp. 1–20) and Nemecek and Kägi (2007); in more detail, two different phosphorus emissions into water were considered:

- Leaching to ground water: assessed using a factor of 0.07 kg P ha^{-1}·$year^{-1}$; and
- Run-off to surface water: evaluated considering 0.175 kg P ha^{-1}·$year^{-1}$, as an emission factor.

Due to a lack of data about the fraction of the eroded soil, phosphate emissions through erosion to surface waters were not included. The latter assumption was considered applicable in this study, considering the slope and soil texture of the area. Detailed information about soil characteristics was reported in Guido et al. (2020).

The emissions of active ingredients related to pesticide application were modelled as 90% emitted to the agricultural soil compartment, 9% emitted to air and 1% emitted to water according to the Product Category Rules for Arable and Vegetable Crops (Environdec, 2020).

Table 2
Emission factors recorded during the field tests for ammonia volatilisation.

Scenario	Ammonia emissions	
	kg NH_3•ha^{-1}	% of nitrogen applied
RS-P	68.69	11.57
FS-P	20.25	4.77
RS-D	68.69	11.57
FS-D	11.59	2.73

Background data for manufacture and supply of seeds, fertilisers and pesticides, fuels, electricity, agricultural mechanised processes and transports, and the related manufacture, supply, maintenance, and end-of-life disposal of machinery were sourced from the Ecoinvent® database v. 3.9, with allocation at the point of substitution as a system model (Moreno-Ruiz et al., 2022; Weidema et al., 2013). For the different mechanised field operations, detailed modelling based on primary data was carried out. Therefore, the processes retrieved from the database were modified considering machinery characteristics (mass, power) and operating parameters (such as working width and speed and total worked area) (Lovarelli & Bacenetti, 2017). The exhaust gas emissions from fuel combustion were modified by scaling them according to reported consumption. The database processes related to the virtual consumption of agricultural machinery included the impacts related to their manufacture, maintenance (e.g., lubricant oil consumption) and disposal (Nemecek & Kägi, 2007).

Regarding the separation process of digestate and the subsequent treatment of the liquid fraction (filtration) (Fig. 1), the vibrating screens installed in the two fertigation scenarios, made of stainless steel, were similar but characterised by different sizes. The one in FS-P had a mass of 1200 kg, while the one in FS-D was heavier (2000 kg); a 10-year life span was considered for both devices. Regarding the annual working time, 800 h $year^{-1}$ was considered for FS-P and 930 h $year^{-1}$ for FS-D. The functioning of the separation systems was monitored at each fertigation event by recording digestate volumes and flow rates, manure characteristics, and electricity consumption. Specifically, the consumption of electric energy was measured only for PU2, as this was the only unit specifically installed to produce a filtered fraction suitable for fertigation, given that PU1 was already installed on the four farms. An electricity metre was installed to detect the electric consumption of the engines that operated the vibrating screen and the loading pumps feeding them. The electric consumption reported for the mass of digestate outflow (LF2) from the separation equipment was equal to 0.26 kWh•t^{-1} of LF2 in farm 1 (FS–P) and 0.36 kWh•t^{-1} of LF2 in farm 2 (FS-D).

These data were used to evaluate system performance through the calculation of mass balances and separation efficiency indexes. Tables 3 and 4 report the main inventory data for the different scenarios.

2.3. *Impact assessment*

The inventory dataset was characterised by means of the composite method recommended by the International Reference Life Cycle Data System (ILCD) (EC-JRC, 2012). The following impact categories were considered: climate change (CC; kg CO_2 eq), ozone depletion (OD; kg CFC-11 eq), particulate matter (PM; kg PM2.5 eq), human toxicity with a carcinogenic effect (HTc; CTUh), human toxicity with no carcinogenic effect (HTnc; CTUh), photochemical ozone formation (POF; kg NMVOC eq), terrestrial acidification (TA; molc H+ eq), terrestrial eutrophication (TE; molc N eq), freshwater eutrophication (FE; kg P eq), marine eutrophication (ME; kg N eq), freshwater ecotoxicity (FEx; CTUe), and mineral and fossil resource depletion (MFRD; kg Sb eq).

2.4. *Sensitivity and uncertainty analysis*

The results of LCA studies depend on the methodological choices, as well as the assumptions made (e.g., concerning the modelling of the emissions). Sensitivity analysis and uncertainty analysis were carried out to investigate the effect of methodological choices and assumptions, as well as the effect of model imprecision and variability of data on the environmental results.

To investigate how the environmental results were affected by these choices, a sensitivity analysis was carried out regarding the following aspects:

Table 3
Inventory data for the cultivation of 1 ha in the different pivot scenarios: RS-P and FS-P.

Scenario	Field Operation	Rep[1]	Time[2] (h•ha^{-1})	Tractor engine power (kW)	Tractor mass (kg)	Equipment	Fuel or electricity consumption	Additional information
RS	Pre-seeding fertilisation	1	0.6	150	7400	Slurry tank with splash plate, 16.7 m^3	23.3 l ha^{-1}	
FS	Pre-seeding fertilisation	1	0.80	135	7750	Slurry tank with 5 anchors for digestate injection	34.5 l ha^{-1}	
RS&FS	Ripping	1	1.0	190	7790	Subsoiler, 7 anchors, ww[3] = 4 m	30 l ha^{-1}	
RS&FS	Soil tillage	1	2.0	150	7400	Combined soil tillage machine, 5000 kg, 10 cm depth	13.5 l ha^{-1}	
RS&FS	Sowing	1	0.50	95	5300	Pneumatic seeder, 8 lines	12 l ha^{-1}	75,000 plants•ha^{-1}
RS&FS	Chemical weed control	1	0.30	60	3650	Sprayer, ww = 14 m	3.5 l ha^{-1}	4 kg ha^{-1} Lumax[4]
RS	Irrigation	10	1.89	n/a	n/a	Pivot + submerged 23.4 kW-pump	441.5 kWh•ha^{-1}	
FS	Irrigation	4	1.89	n/a	n/a	Pivot + submerged 23.4 kW-pump	176.6 kWh•ha^{-1}	
FS	Fertigation	6	2.50	n/a	n/a	Vibrating screen	27.4 kWh•ha^{-1}	
FS	Fertigation	6	1.89	n/a	n/a	Pivot + Vibrating screen + submerged 23.4 kW-pump	287.9 kWh•ha^{-1}	
RS&FS	Chemical pest control	1	0.1	n/a	n/a	Self-propelled sprayer, 110 kW, ww = 24 m, 5800 kg	4.2 l ha^{-1}	0.3 kg ha^{-1} Ampligo[5]
RS&FS	Harvesting	1	0.5	n/a	n/a	Combine forager, 460 kW, 8 lines, 14240 kg	56 l ha^{-1}	51.9 t ha^{-1} [6]
RS&FS	Biomass transport	1	n/a	225	10400	3 Farm trailers 32 m^3, 3 axles	n/a	

Note: [1] Rep = Number of interventions per ha; [2] working time per each intervention, [3] ww = working width; [4] = S-Metolachlor 27.10%, Atrazine 10.15%, Mesotrione 2.71%; [5] = 9.26% Chlorantraniliprole, 4.63% Lambda-Cyhalothrin; [6] = fresh matter of chopped maize (dry matter = 33% of fresh matter), no significant difference between the two scenarios.

Table 4
Inventory data for the cultivation of 1 ha in the different pivot scenarios: RS-D and FS-D.

Scenario	Field Operation	Rep[1]	Time[2] (h•ha^{-1})	Tractor engine power (kW)	Tractor mass (kg)	Equipment	Fuel or electricity consumption	Additional information
RS	Ripping	1	0.80	140	6500	Disch harrow, 30 cm depth	30.0 l ha^{-1}	
RS	Pre-seeding fertilisation	1	0.60	158	7150	Slurry tank with splash plate, 16.7 m^3	18.0 l ha^{-1}	
FS	Pre-seeding fertilisation	1	0.80	248	9750	Hose-reels with 5-anchors trolley (ww[3] = 2.5m)	24.0 l ha^{-1}	
RS	Soil tillage - Harrowing	1	1.20	140	6500	Rotary harrow, ww[3] = 6 m, 10 cm depth	30.0 l ha^{-1}	
FS	Soil tillage – Harrowing	1	1.00	140	6500	Rotary harrow, ww[3] = 6 m, 10 cm depth	25.0 l ha^{-1}	
RS&FS	Sowing	1	0.70	85	4800	Pneumatic seeder, 6 lines	10.5 l ha^{-1}	75000 plants•ha^{-1}
RS	Irrigation	8	5.00	n/a	n/a	Drip irrigation + 40.6 kW-pump	1638.4 kWh•ha^{-1}	
FS	Irrigation	4	5.00	n/a	n/a	Drip irrigation + 40.6 kW-pump	818.4 kWh•ha^{-1}	
FS	Fertigation - water[4]	4	5.00	n/a	n/a	Drip irrigation + 40.6 kW-pump	818.4 kWh•ha^{-1}	
FS	Fertigation - liquid fraction [4]	4	3.4	n/a	n/a	Vibrating screen + 5.95 kW-pump	80.0 kWh•ha^{-1}	
RS&FS	Harvesting	1	0.5	n/a	n/a	Combine forager, 580 kW, 8 lines, 13500 kg	52.5 l ha^{-1}	51.9 t ha^{-1} [5]
RS&FS	Biomass transport	1	n/a	225	10400	3 Farm trailers 32 m^3, 3 axles	n/a	

Note: [1] Rep = Number of interventions per ha; [2] working time per each intervention, [3] ww = working width; [4] = fertigation is divided because the timing of water distribution and liquid fraction injection is different; [5] = fresh matter of chopped maize (dry matter = 33% of fresh matter), no significant difference between the two scenarios.

- The LCIA (Life Cycle Impact Assessment) method used to characterise the inventory. In this regard, in addition to the use of the ILCD method, the EF 3.0 and the ReCiPe 2016 Midpoint (H) V1.07/World (2010) H methods were also considered. The EF method was the impact assessment method adopted in the Environmental Footprint transition phase of the European Commission. The implementation was based on EF method 3.0, published for use during the EF transition phase (Fazio et al., 2018; Sala et al., 2018). ReCiPe was developed by the Dutch Research Institute of RIVM (National Institute for Public Health and the Environment), Radboud University Nijmegen, Leiden University and PRé Consultants in 2008. It was updated to its current version in 2016 (Huijbregts et al., 2017). It is one of the characterisation methods with the greatest range of applications, as it contains global characterisation factors, which is why it is also currently one of the most widely used;
- The characterisation factor for ammonia using the regionalised factor for Italy instead of the global one was used;

- The modelling of the emission of N compounds, considering the variability of ammonia emissions, was observed during the field trials. In detail, the ammonia emissions were estimated using the minimum and maximum values recorded in the field, while the emissions of nitrate and dinitrogen monoxide were re-calculated considering that variation in NH_3 losses.

Uncertainty analysis was carried out using the Monte Carlo technique (1000 iterations and a confidence interval of 95%) to test the robustness of the achieved results concerning the comparison between the reference and the corresponding fertigation scenarios (RS-P and FS-P; RS-D and FS-D).

3. Results

3.1. Environmental impact

Table 5 reports the absolute environmental results for the evaluated impact categories for the different scenarios, while Fig. 3 shows the relative variation between the fertigation scenarios (FS–P and FS-D) and the reference scenarios (RS-P and RS-D).

The comparison between irrigation and fertigation techniques in the two farms does not present a clear indication of the best environmentally performing technique. In detail, for 5 impact categories, the cultivation with pivot showed better environmental results (impact reduction ranging from 0.9 to 31.5%). For 3 environmental effects, maize grown with drip irrigation presented a lower impact. For the remaining 4 impacts, the cultivation with pivot was less impacting for the reference scenarios, while cultivation with drip irrigation was the best performing for the fertigation scenarios. These differences were not strictly related to the adopted irrigation and fertigation solutions but to the different cultivation practices. For example, for freshwater ecotoxicity, the higher impact of cultivation with pivot was related to the application of plant protection products (herbicide and insecticide) that were not used in the case of drip irrigation. For the impact categories more strictly related to ammonia emissions, higher impact reductions with respect to the reference scenario were achieved in the case of drip irrigation, suggesting that this technique allowed the maximisation of fertigation benefits.

Table 5
Absolute environmental results for the selected FU (1 tonne of dry matter).

Impact category	Unit	RS-P	FS-P	RS-D	FS-D
Climate change (CC)	kg CO_2 eq	201.0	171.9	219.6	194.1
Ozone depletion (OD)	kg CFC-11 eq	$9.11 \bullet 10^{-06}$	$9.44 \bullet 10^{-06}$	$1.10 \bullet 10^{-05}$	$1.14 \bullet 10^{-05}$
Human toxicity, non-cancer effects (HT-noc)	CTUh	$7.43 \bullet 10^{-05}$	$7.55 \bullet 10^{-05}$	$5.88 \bullet 10^{-05}$	$5.91 \bullet 10^{-05}$
Human toxicity, cancer effects (HT-c)	CTUh	$2.40 \bullet 10^{-06}$	$2.88 \bullet 10^{-06}$	$3.15 \bullet 10^{-06}$	$3.90 \bullet 10^{-06}$
Particulate matter (PM)	kg PM2.5 eq	0.297	0.111	0.299	0.081
Photochemical ozone formation (POF)	kg NMVOC eq	0.492	0.494	0.477	0.477
Acidification (TA)	molc H+ eq	12.49	4.04	12.53	2.56
Terrestrial eutrophication (TE)	molc N eq	55.42	17.62	55.40	10.82
Freshwater eutrophication (FE)	g P eq	42.12	42.74	49.95	50.94
Marine eutrophication (ME)	kg N eq	10.96	5.98	10.95	6.38
Freshwater ecotoxicity (Fex)	CTUe	3626	3811	1152	1409
Mineral, fossil & ren resource depletion (MFRD)	g Sb eq	1.495	1.724	1.544	1.801

Regarding the relative comparison between reference and fertigation scenarios (RS-P *vs* FS-P and RS-D *vs* FS-D),

- For 5 of the 12 evaluated impact categories, the fertigation scenarios involved an impact reduction ranging from 14.5 to 68.2% when the pivot was used and from 11.6 to 80.5% when irrigation and fertigation were carried out with a drip irrigation system. For these impact categories, the benefits related to the adoption of fertigation were higher than the increase due to the liquid fraction treatment (additional electricity consumption and the manufacturing of the vibrating screen). Higher impact reductions were achieved for the impact categories more affected by ammonia emissions (PM, TA and TE). Between pivot and drip irrigation, fertigation benefits were more noticeable in the latter. For ME, the impact reduction ranged from 40 to 45% and was linked to the optimisation of the amount of N supplied in the different scenarios. Because this impact was deeply affected by the nitrate emissions, the application for FSs of the same amount of N as for RSs would involve an impact increase due to higher nitrate leaching. In fact, without optimisation of N supply, if less N was lost due to ammonia volatilisation and the N crop removal was constant due to the same biomass yield, the nitrate leaching increased;
- For the 4 impact categories (i.e., OD, HT-noc, POF and FE), the impact variation was small, ranging from −0.10% to +5.10%. For these environmental effects, the benefits due to ammonia reduction were offset by operation of the vibrating screen;
- For the last 3 impact categories (HT-c, FEx and MFRD), the fertigation scenarios showed higher environmental impacts. This was mainly due to the manufacturing of the vibrating screen and only secondarily to additional electricity consumption for the treatment of the digestate liquid fraction. For MFRD, a share of the impact increase was also related to the higher fuel consumption for pre-seeding organic fertilisation (injection instead of surface application with splash plate).

3.2. Contribution analysis

The contribution analysis for the four scenarios is reported in Table 6. The analysis of the contributions showed similar trends among all scenarios evaluated, even if some differences were highlighted. The absence of the construction of the vibrating screen was noted in the traditional fertilisation and irrigation scenarios, FS-P and FS-D.

In more detail, the contribution analysis showed the following:

- The mechanisation of field operations was responsible for the main share of the environmental impact on OD in FS-P and FS-P (about 74%), but it impacted RS-D and FS-D less (41–43%). It was also the main hotspot in HTnoc (over 90% in FS-P and FS-P, 81–83% in RS-D and FS-D), POF (about 90% in FS-P and FS-P, about 76–78% in RS-D and FS-D), and MFRD (83–86% in FS-P and FS-P, 73–78% in RS-D and FS-D, where no pesticides were applied). Finally, it was relevant in HTc (57–69% in FS-P and FS-P, 33–42% in RS-D and FS-D);
- The manufacture of the vibrating screen showed a contribution <2% for 9 of 12 evaluated impact categories, but its role could not be negated for HT-c (>15% in both FSs mainly due to the production process of steel and the management of its wastes), FEx (from 3.3% in FS-P to 13.8% in FS-D mainly due to the manufacturing of the pump) and MFRD (from 4.7% in FS-P to 7.1% in FS-D, mainly due to the consumption of the ferronickel used to produce steel). Not coincidentally, these three impact categories were those in which the FSs showed a higher impact than the RSs.

- In RS-D and FS-D, the manufacture of the irrigation pump used for drip irrigation played a relevant role for FEx (36–44%) and HTc (about 9%).

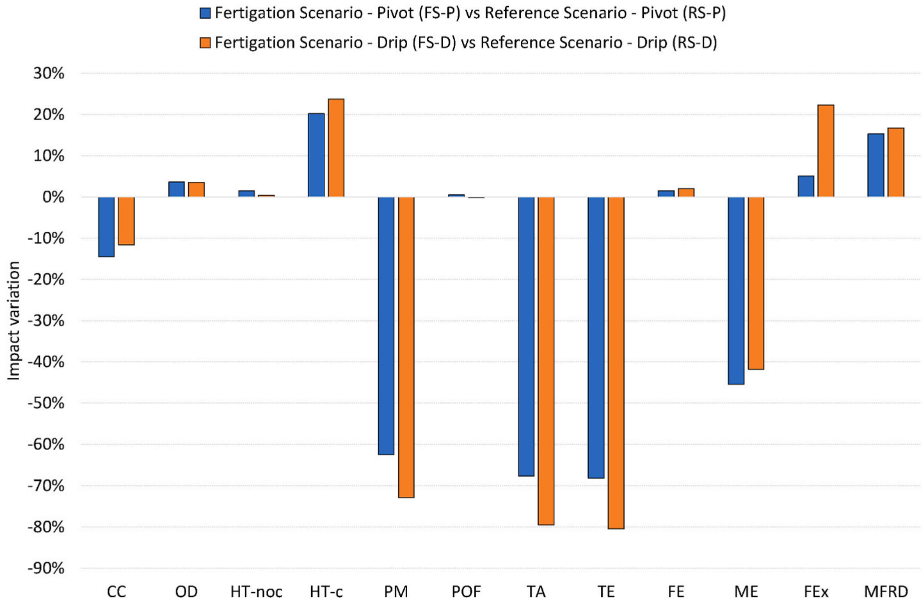

Fig. 3. Impact variation (Δ) between reference and fertigation scenarios.

Table 6
Contribution analysis results: Percentage of the total impact related to the output from different inputs.

Contributor	Scenario	CC	OD	HT-noc	HT-c	PM	POF	TA	TE	FE	ME	FEx	MFRD
Mechanisation[1]	RS-P	22.2	73.7	94.0	68.8	7.8	91.4	2.9	3.0	10.7	1.4	7.4	86.1
	FS-P	25.6	72.2	92.8	56.6	20.9	90.4	9.0	9.3	10.3	2.5	8.3	82.8
	RS-D	14.5	42.3	83.5	41.5	6.4	77.9	2.4	2.5	7.6	1.1	21.2	77.8
	FS-D	15.9	41.1	81.1	32.5	23.3	76.1	11.3	12.3	7.2	1.9	20.5	73.2
Electricity[2]	RS-P	6.1	18.4	2.5	16.3	1.2	5.4	0.5	0.2	7.8	0.1	2.8	4.2
	FS-P	8.0	19.8	2.7	15.1	3.7	6.0	1.6	0.6	8.6	0.2	3.0	4.0
	RS-D	20.7	56.4	11.7	46.0	4.6	20.7	1.7	0.7	24.5	0.3	32.8	15.0
	FS-D	24.6	57.1	12.2	39.0	17.8	21.7	8.9	3.6	25.2	0.6	28.2	13.5
Other prod. Factors[3]	RS-P	2.6	4.6	2.2	6.9	0.9	2.0	0.3	0.1	1.8	0.3	2.3	5.7
	FS-P	2.6	4.4	2.2	5.8	2.4	2.0	0.9	0.3	1.8	0.5	2.2	4.9
	RS-D	2.0	1.1	2.3	3.5	0.2	1.0	0.1	0.1	0.8	0.3	1.9	3.3
	FS-D	2.0	1.0	2.2	2.8	0.9	1.0	0.4	0.3	0.7	0.5	1.6	2.8
Irrigation Pump[4]	RS-P	0.1	0.2	1.0	5.7	0.1	0.2	0.0	0.0	0.8	0.0	6.7	1.9
	FS-P	0.1	0.2	1.0	4.7	0.3	0.2	0.1	0.0	0.8	0.0	6.4	1.7
	RS-D	0.2	0.3	2.6	9.0	0.3	0.4	0.1	0.0	1.4	0.0	44.0	3.9
	FS-D	0.2	0.3	2.6	7.3	1.0	0.4	0.3	0.1	1.4	0.0	36.0	3.4
Vibrating screen[4]	RS-P	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	FS-P	0.3	0.3	0.9	15.9	0.9	0.5	0.1	0.0	0.8	0.0	3.3	4.7
	RS-D	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	FS-D	0.5	0.4	1.9	18.4	1.9	0.8	0.3	0.1	1.0	0.0	13.8	7.1
Emissions of Nitrogen & Phosporous compounds	RS-P	68.6	0.0	0.0	0.0	89.3	0.0	96.1	96.8	78.0	98.2	0.0	0.0
	FS-P	62.7	0.0	0.0	0.0	70.1	0.0	87.6	89.7	76.9	96.8	0.0	0.0
	RS-D	62.6	0.0	0.0	0.0	88.5	0.0	95.8	96.8	65.7	98.3	0.0	0.0
	FS-D	56.8	0.0	0.0	0.0	55.1	0.0	78.9	83.5	64.4	97.0	0.0	0.0
Emissions of pesticide	RS-P	0.5	3.2	0.4	2.2	0.6	1.0	0.2	0.0	0.8	0.0	80.9	2.1
	FS-P	0.6	3.1	0.4	1.8	1.7	1.0	0.7	0.1	0.8	0.0	76.9	1.8
	RS-D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	FS-D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Note: [1] The label "*Mechanisation*" groups the impact of the different field operations; [2] Includes all the electricity consumptions (irrigation and, in the fertigation scenarios, liquid fraction treatment and fertigation); [3] The label "*Other prod. factor*" includes the contribution of seeds, fertilisers and pesticides; [4] Includes only the manufacturing of the devices.

- The item "electricity" in the table refers to electricity consumption for the treatment of the liquid fraction of digestate, as well as for irrigation. In absolute terms, this impact was greater for the fertigation scenarios and, for most of the evaluated impact categories, also in relative terms. For HT-c and MFRD in the 4 scenarios and, for FEx, in the drip scenarios, the relative contribution of electricity was smaller in the fertigation scenarios than in the reference scenarios. This is because, for the FSs, an additional input was considered (the vibrating screen). Between the pivot and drip irrigation scenarios, the latter showed a higher electricity contribution to the total impact. In fact, in RS-P and FS-P, it never exceeded 10% in any of the evaluated categories, except for OD (about 20% in both scenarios) and HT-c (about 15–16%), while in RS-D and FS-D, electricity deeply affected OD (56–58%), HTc (39–46%), FE (about 25% for both scenarios), FEx (28–33%) and CC (21–25%).

- For all scenarios, the emissions of N and P compounds were mainly responsible for CC (about 60–70%), mainly due to dinitrogen monoxide emission; PM (from 55 to 89%), TA (79–96%), TE (84–97%) and FE (64–78%) mainly due to ammonia emission; and ME (not less than 95%) mainly due to nitrate leaching. These emissions remained the main ones responsible for PM, TA and FE, both in reference and fertigation scenarios; however, in the latter, the reduction of the ammonia emissions related to the adoption of fertigation was appreciated because the relative contribution was lower.
- For FEx, in the two scenarios with pivot (RS-P and FS-P), the key environmental aspect was the emission of the pesticides' active ingredients, while for the two drip irrigation scenarios (RS-D and FS-D), where no plant protection products were applied, most of the impact was related to pollutant emissions in the exhaust gas of the tractor engines.

3.3. Sensitivity analysis results

As explained in Section 2.4, sensitivity analysis was carried out about the emission factor of N compounds, the impact assessment method and the characterisation factors for ammonia.

Table 7 reports the inventory data used regarding N compound emissions.

The LCA results achieved using the EF 3.0 and ReCiPe 2016 Midpoint (H) V1.07/World (2010) H LCIA methods (reported in the supplementary material Table S1 and S2), despite some impact categories having different units of measure and some characterisation factors being different, confirmed the results achieved using the ILCD midpoint LCIA method regarding the relative comparison among the different scenarios (Fig. S1 in the supplementary material). In particular, the fertigation scenarios showed a lower impact with respect to the reference scenarios for acidification (−68% for FS-P *vs* RS-P, −80% for FS-S *vs* RS-D), marine eutrophication (−45% for FS-P *vs* RS-P, −41% for FS-S *vs* RS-D) and fine particulate matter formation (−62% for FS-P *vs* RS-P, −73% for FS-S *vs* RS-D).

Table 8 and Fig. S2 (supplementary material) report the results of the sensitivity analysis regarding the use of different ammonia emission factors recorded during the field trials, as well as using the regionalised characterisation factor for ammonia. For the impact categories affected, Table 8 shows the impact variation with respect to the results reported in Table 5. When the minimum and maximum emission factors for ammonia were considered, in addition to NH_3, the emissions of NO_3 and N_2O were also affected, and consequently, the impact on climate change varied. Even if the impact variation was not the same for the different scenarios, some general conclusions could be made: (i) Particulate matter, acidification and terrestrial eutrophication were the impact categories showing greater impact variation because they were directly affected by the variation in ammonia emissions; (ii) when the NH_3 emissions increase, N_2O emissions and NO_3 leaching were reduced and, consequently, an impact reduction occurred for climate change (from 0.72 to 4.65%) and marine eutrophication (from 2.89 to 13.08%). In contrast, when the ammonia emissions were lower, a higher share of the N was lost as dinitrogen monoxide (climate change increased to 6.28%) and nitrate (marine eutrophication increased to 15.74%). These results highlight the importance of calibrating fertilisation according to the expected losses due to ammonia volatilisation. Otherwise, the risk is that of reducing losses due to volatilisation but, at the same time, increasing the leaching of nitrates and denitrification of N.

Table 7
Inventory data used in the sensitivity analysis of nitrogen compound emissions (* share of the nitrogen applied).

NH_3 emission Value	Nitrogen Compound	Reference scenario	Fertigation scenario pivot	Fertigation scenario drip
Average	NH_3	11.57%* 68.68 kg ha^{-1}	4.77%* 20.25 kg ha^{-1}	2.37%* 11.59 kg ha^{-1}
Minimum		5.34%* 31.70 kg ha^{-1}	1.46%* 6.20 kg ha^{-1}	2.17%* 9.21 kg ha^{-1}
Maximum		16.25%* 96.47 kg ha^{-1}	8.72%* 37.01 kg ha^{-1}	3.66%* 15.54 kg ha^{-1}
Average	N_2O	8.25 kg ha^{-1}	6.47 kg ha^{-1}	6.64 kg ha^{-1}
Minimum		8.98 kg ha^{-1}	6.74 kg ha^{-1}	6.69 kg ha^{-1}
Maximum		7.71 kg ha^{-1}	6.14 kg ha^{-1}	6.56 kg ha^{-1}
Average	NO_3	795.54 kg ha^{-1}	434.28 kg ha^{-1}	468.69 kg ha^{-1}
Minimum		942.52 kg ha^{-1}	490.09 kg ha^{-1}	478.13 kg ha^{-1}
Maximum		685.09 kg ha^{-1}	367.63 kg ha^{-1}	452.97 kg ha^{-1}

The use of the regionalised characterisation factor deeply affected particulate matter, acidification and terrestrial eutrophication, which were deeply reduced and had a slight effect on marine eutrophication. The impact variation was proportional to the variation of the ammonia characterisation factor for the above-mentioned impact categories (e.g., the regionalised characterisation factor was 25 times lower than the unregionalised one, 0.12 molc H+ eq./kg of ammonia and 3.02 molc H+ eq./kg of ammonia). Regarding the comparison between the reference and the fertigation scenarios, the use of the characterisation factors for ammonia made the benefits related to the adoption of the fertigation techniques less evident.

3.4. Uncertainty analysis results

The uncertainty analysis results showed that both for the pivot (Fig. S3) and drip irrigation (Fig. S4) scenarios, there was a small uncertainty level (lower than 0.5%) for all evaluated impact categories except for human toxicity and non-cancer effects (HT-noc), where the difference between RS-P and FS-P was mainly related to the uncertainty of the inventory data. The results of the uncertainty analysis showed that the uncertainty due to selection of the data from databases, model imprecision and data variability did not significantly affect the environmental results for all impact categories, except HT-noc.

4. Discussion

This study represents the first application of LCA to two different fertigation techniques in an arable crop. The interesting environmental results coupled with positive economic performance (see subsection 4.3) confirmed the suitability of fertigation as an interesting mitigation solution to the environmental impact due to organic fertiliser utilisation in arable crops. Using fertigation, the environmental impact was reduced thanks to increased nutrient efficiency contributing to the achievement of the objectives of environmental strategies (such as from Farm to Fork).

In the following section, the main limitations of the study are discussed, a comparison with previous LCA studies carried out on maize cultivation is reported and the economic performance of the two fertigation techniques is briefly presented. More details about practical recommendations for fertigation application can be found in the Supplementary materials.

4.1. Limitations of the study

LCA is defined by two ISO standards and can be carried out with the support of guidelines and recommendations. Despite this, the practical application of LCA to real case studies faces difficulties (e.g., lack of data availability and money and time constriction) that cannot make strict

Table 8

Results of the sensitivity analysis: Impact variation (respect to the results reported in Table 5) considering the maximum (**Max**) and minimum (**Min**) values recorded during the field tests and the regionalised characterisation factor for ammonia (**Reg**).

Impact category	RS-P			FS-P			RS-D			FS-D		
	Max	Min	Reg	Max	Min	Reg	Max	Min	Reg	Max	Min	Reg
Climate change	−4.65%	6.28%	0.00%	−3.31%	2.71%	0.00%	−4.29%	5.79%	0.00%	−0.72%	0.45%	0.00%
Particulate matter	35.89%	−47.75%	−88.69%	57.05%	−47.76%	−68.85%	35.80%	−47.64%	−88.48%	18.83%	−11.27%	−55.05%
Acidification	38.86%	−51.71%	−92.23%	72.48%	−60.68%	−84.01%	38.83%	−51.67%	−92.14%	27.23%	−16.30%	−76.46%
Terrestrial eutrophication	39.16%	−52.11%	−36.82%	74.35%	−62.25%	−34.15%	39.21%	−52.17%	−36.87%	28.72%	−17.19%	−31.95%
Marine eutrophication	−11.83%	15.74%	−3.34%	−13.08%	10.95%	−1.80%	−11.83%	15.75%	−3.34%	−2.89%	1.74%	−0.97%

Note: The regionalised characterisation factor for ammonia was 0 for the impact category particulate matter.

adherence to standards and protocols possible. This study was carried out following the ISO standards for LCA and, when mentioned (e.g., for the modelling of the emission from pesticide applications), the PCR for arable crops (Environdec, 2020). Despite this, the following limitations should be considered both for a correct interpretation of results and for the identification of future improvements:

- One growing season was considered. Although that season can be considered representative of the most common weather conditions of the studied area, it should be considered that in years with a higher temperature, strong thunderstorms, hail or reduced water availability, the crop yield could be affected; consequently, the environmental results would also differ. In this regard, the results of this study should be confirmed by analysing more subsequent growing seasons;
- The infrastructure of the two irrigation systems was excluded from the system boundaries due to the lack of inventory data and because the aim of the study was the comparison of maize cultivation with or without fertigation (and not the comparison among different irrigation systems). This exclusion does not affect the relative comparison between the reference and the fertigation scenarios but makes the comparison of the absolute results of the pivot scenarios inconsistent with those of the drip scenarios. For a comparison of the absolute results, this capital good should be included in the system boundary, as well as in the disposal of the drip lines that are installed at the beginning of the year in the drip scenarios.

However, the previously discussed limitations could surely affect the absolute environmental results but would have less effect on the results related to fertigation and, in particular, on the relative comparison of the maize crop with or without this technique. The benefits of fertigation could vary depending on the temperature, wind and rainfall of the growing season.

4.2. Comparison with previous LCA studies

Until now, few/no attention has been given to the evaluation of fertigation by LCA. LCA has been applied to evaluate fertigation in soilless tomato cultivation in greenhouses in Tunisia (Maaoui et al., 2021) and as a possible disposal solution for bioethanol stillage in Brazil (Rocha et al., 2010). However, no LCA studies have evaluated the possible benefits related to fertigation in terms of emission reduction. As already mentioned in the Introduction, in recent years, LCA has been widely applied to crop cultivation. Despite this, a direct comparison with the absolute environmental results achieved in previous LCA studies focused on maize is not possible. The selection of different functional units (area, mass of dry matter and fresh matter), the definition of different system boundaries, and the choice of diverse allocation procedures or models make the comparison unreliable. Nevertheless, the results of the contribution analysis can be compared. In this regard, the results of this study agree with previous LCAs in maize regarding: (i) the identification of ammonia emissions as one of the main factors responsible for terrestrial acidification, particular matter formation and terrestrial eutrophication (Bacenetti & Fusi, 2015; Fantin et al., 2017; Supasri et al., 2020; Zhang et al., 2018), (ii) the effectiveness of ammonia emission reduction as a mitigation solution of the above mentioned impact categories (Boone et al., 2016; Gaglio et al., 2019; Noya et al., 2018), the possible presence of a trade-off between the reduction of ammonia and the increase in N leaching (Bacenetti et al., 2016; Noya et al., 2015).

4.3. Economic aspects

Although this study focuses on the environmental performance of fertigation techniques, the sustainability analysis of this solution should also consider the economic dimension. In this regard, from an economical point of view, the fertigation cost can be estimated at 1.2 €•m^{-3} of digestate applied for pivot irrigation and 1.3 €•m^{-3} of digestate applied for drip irrigation, without considering depreciation that can be 8000–9000 €•year^{-1} for the filtration equipment and pumping system. The total cost depends on the total area irrigated. Considering that the area that can be served by a filtration system can be 100 ha for drip irrigation and 150 ha for pivot, the total cost with these areas can be 100 € and 135 €, respectively. These values do not include the cost of the irrigation system but only the additional equipment required to filter and inject the slurry into the irrigation water. It must be considered that the costs of fertigation are comparable to the operations required to apply digestate to the fields; therefore, the systems can be conveniently implemented in normal agricultural practices. The fertigation system, once in place, can also be used for other crops, allowing the application of digestate to the crops during their growth and therefore increasing nutrient efficiency and reducing the environmental impact. The extent of the reduction depends on applied organic fertilisers and hence on crop nutrient requirements. However, with similar applications of organic fertilisers, a similar impact reduction could also be achieved for other crops.

More details about the above-reported figures and about the economic sustainability of fertigation techniques can be found in Quílez et al. (2021). The implementation of fertigation with digestate is therefore suitable in all situations where a low-pressure sprinkler or drip irrigation system is already in place. Furthermore, fertigation can promote the use of irrigation systems with high water efficiency in areas such as Lombardy (Italy), where the most used irrigation systems are surface flow and sprinkling.

5. Conclusions

This study analysed maize cultivation with an emerging organic fertilisation management technique, i.e., pre-seeding injection, followed by side-dressing fertigation, with an LCA approach. The comparison at two farms between a reference cultivation scenario and alternative management (one with fertigation practiced via pivot and one via drip irrigation) made it possible to measure the effective impact reduction obtainable due to its adoption. In fact, the results, expressed per tonne of dry matter produced, clearly indicate that alternative fertilisation management (i.e., fertigation) leads to important benefits on acidification, particulate formation and eutrophication, reduced by up to about 80% compared to the reference fertilisation scenario, which is an excellent result, especially if production is contextualised in an area under strong environmental pressure, such as Po Valley. The mitigation of the climate change impact, which was between 12 and 14%, was also an interesting result. A trade-off was identified in the increased impact on the consumption of fossil and mineral resources (13–17%) due to construction and operation in alternative fertilisation management scenarios of a vibrating screen capable of highly efficient solid–liquid separation to allow fertigation. These results underline the good prospects of introducing this technology within this management context. Future efforts should be aimed at energy and construction efficiency measures of digestate treatments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biosystemseng.2023.10.007.

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