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Research article

Optimizing application of dairy effluent with synthetic N fertilizer reduced nitrogen leaching in clay loam soil

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ABSTRACT

High application rates of dairy effluent and manure are often associated with nitrogen (N) leaching, which can affect groundwater quality. Here, we used a lysimeter to examine N leaching losses and biomass yield following application of dairy effluent and manure under wheat-maize cropping. The field experiment included seven treatments: no N fertilizer (Control); 200/300 kg N ha^{-1} synthetic N fertilizer only (wheat/maize) (CN); 100/150 kg N ha^{-1} synthetic N fertilizer plus 100/150 (DE1), 150/200 (DE2) and 250/350 (DE3) kg N ha^{-1} dairy effluent; 100/150 kg N ha^{-1} synthetic fertilizer plus 100/150 kg N ha^{-1} dairy manure (SM1); and 150/225 kg N ha^{-1} synthetic fertilizer plus 50/75 kg N ha^{-1} dairy manure (SM2). Compared with CN, DE1 treatment increased maize yield by 10.0 %, wheat N use efficiency (NUE) by 26.5 %, and wheat and maize N uptake by 7.7–16.3 %, while reduced N leaching by 22.4 % in wheat season and by 40.4 % in the maize season. In contrast, DE2 and DE3 treatment increased N leaching by 27.2–241 % and reduced NUE by 26.2–55.2 %. SM2 treatment increased yield and NUE by 8.8 % and 7.8 %, respectively, and reduced N leaching by 42.9 % during the wheat but not the maize season. Annual N leaching losses were 37.6 kg N ha^{-1} under CN treatment, but decreased to 27.4 kg N ha^{-1} under DE1. In contrast, N leaching increased to 52.8 and 84.1 kg N ha^{-1} under DE2 and DE3 treatment, respectively ($P < 0.05$). Meanwhile, under SM1 and SM2 treatment, N leaching decreased by 71.2 % and 32.0 %, respectively, compared with CN. These results suggest that replacing 50 % and 25 % synthetic N fertilizer with dairy farm effluent and manure could reduce N leaching losses but had varied effects on crop productivity under wheat-maize cropping.

1. Introduction

Indiscriminate and excessive application of synthetic N fertilizer in intensive wheat-maize cropping systems has resulted in

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substantial nitrogen (N) losses through leaching and gaseous emissions, leading to air pollution and surface and groundwater contamination [1]. In most upland soils, nitrate (NO_3^-) is the dominant form of available N (89–99 %) for crop uptake; however, it is extremely soluble and readily lost via leaching as soil water moves beyond the root zone [2]. Accordingly, NO_3^- runoff via surface water and leaching into groundwater represent the major pathways of N losses from intensive cropping systems [3], which cause degradation of groundwater quality and surface eutrophication, both of which accelerate biodiversity loss [4]. At the same time, high concentrations of NO_3^- in drinking water can endanger the health of babies and expectant mothers, potentially leading to infantile methemoglobinemia or gastrointestinal cancer [5]. Enhanced N use efficiency (NUE) is critical to mitigate N leaching losses from cropping systems.

The middle and lower Yangtze River Plain is one of four major grain-producing areas in China [6]. To increase crop yield and help meet the demands of the increasing population, large amounts of synthetic N fertilizer are often applied in this region. However, the NUEs of wheat and maize grown in this region are thought to be as low as 28.0 % and 26.2 %, respectively [7]. To improve NUE and increase silage production while mitigating NO_3^- leaching [8], optimizing synthetic N management together with organic fertilizer application has been proposed as a substitute for synthetic N fertilizer [9]. Lu et al. [10] and Wang et al. [11] suggested that 150–240 kg N ha^{-1} is the optimum N fertilizer application rate for wheat and maize cultivation in the Yangtze River Region, while Jiang et al. [12] and Tian et al. [13] recorded maximum wheat and maize yields at an application rate of 180–210 kg N ha^{-1}. Wang et al. [11] and Zhou and Butterbach-Bahl [9] concluded that a 20–60 % decrease in rates of synthetic N fertilizer application on the Yangtze River Delta from 500 to 650 to 180–350 kg N ha^{-1} yr^{-1} could enhance NUE and increase silage production while reducing groundwater NO_3^- contamination.

However, since N dynamics and NO_3^- leaching are influenced by complex factors such as seasonal precipitation, temperature, and evapotranspiration [14], fertilizer type and application rates [15], types of soil and cropping systems [16], and their interactions, the effects of different organic N fertilizers on N leaching remains unclear. Dairy farm effluent and manure are essential sources of plant nutrients, and at present, the average application rate of livestock N in China is 74 kg N ha^{-1} yr^{-1} [17]. Some studies argue that effluent and manure application as substitutes for synthetic fertilizers supplies the soil with adequate amounts of organic matter and available N, thus improving soil structure and fertility, and reducing NO_3^- leaching losses [18]. In contrast, other studies suggest that the application of dairy farm effluent and manure increases NO_3^- concentrations above the World Health Organization (WHO) drinking water standard (11.3 mg N L^{-1}) in wheat-maize cropping [19].

Dairy effluent is a high-quality source of organic liquid N produced via anaerobic fermentation [20] and is known for its quick nutrient resource utilization, efficiency, and potential benefits over soil organic matter. Application of effluents in the field could reduce the hazard of risky events such as drought fashioned climate change [21]. According to Frick et al. [22], effluent-induced NO_3^- leaching in loamy soils is affected by the application rate, with a significant outcome from alfalfa and maize fields at an application rate of 112–202 kg N ha^{-1}, but an increase at rates $\geq$300 kg N ha^{-1} [23]. Meanwhile, Li et al. [24] and Silva et al. [25] reported an increase in NO_3^- leaching from 11.2 to 180.5 kg N ha^{-1} with increasing effluent application rates (200–1000 kg N ha^{-1}). Zhang et al. [26] opined that effluent amendment reduces NO_3^- leaching from loamy soil because effluent organic N is decomposed more slowly, providing a more sustainable supply of nutrients for crop development and increasing the NUE compared with synthetic N fertilizer [27,28]. In contrast, other studies found that NO_3^- leaching increased with increasing soil NH_4^+ concentrations [29], as well as a relatively low C/N (2.0–5.0) ratio [30], low crop NUE [27], and heavy precipitation [31]. These contradictory findings imply that more research is required to determine the optimal proportion of effluent versus synthetic N fertilizer required to lessen NO_3^- leaching and enhance soil fertility.

Livestock manure has been extensively reported to enhance crop production and NUE, while reducing NO_3^- leaching losses when compared to synthetic N fertilizer [32]. However, Chen et al. [33] suggested that manure-induced NO_3^- leaching in grassland caused eutrophication of neighbouring water bodies. Meanwhile, Xia et al. [34] and Zhou et al. [35] reported that partial (40–57 %) replacement of synthetic N fertilizer with livestock manure decreased NO_3^- leaching by 29.1–44.8 % under maize-wheat cropping. Similarly, Liu et al. [8] estimated that replacing 50 % synthetic N fertilizer with dairy manure reduced NO_3^- leaching losses on grassland by 57.0 % compared with synthetic fertilizer alone due to the low rate of manure mineralization. In contrast, the application of cattle manure increased NO_3^- leaching in sandy soil by 23–39 % compared to synthetic fertilizer alone under wheat-maize cropping [36].

Dairy effluent contains various organic and inorganic compounds that can significantly influence soil properties, including the amount of dissolved organic carbon (DOC). High concentrations of DOC in soil can impact soil structure, nutrient availability and microbial activity [15]. Thus, understanding the impact of substituting synthetic N fertilizer with dairy effluent or manure is vital for sustainable land management practices and mitigating potential groundwater contamination. Our study used a lysimeter to investigate the effects of synthetic N fertilizer alone versus combined application with dairy manure and effluent on inorganic N and DOC leaching and silage yield under wheat-maize cropping. The objectives were to (1) identify the impacts of different application rates of manure and effluent on inorganic N (NH_4^+ and NO_3^-) and DOC leaching losses, and (2) determine the optimal application rates of manure and effluent with synthetic N fertilizer in terms of N leaching and yield. We hypothesized that optimal replacement of synthetic N fertilizer with dairy effluent and manure could sustainably mitigate N leaching losses, while increasing silage yield and NUE in wheat-maize cropping.

2. Materials and methods

2.1. Site description and lysimeter establishment

The lysimeter trial was conducted in a typical maize (*Zea mays* L.) - wheat (*Triticum aestivum* L.) cropping field at Luhe in Jiangsu Province, China (32°30′N, 118°37′E). The average annual temperature across a 30-year period was 15.6 °C, minimum and maximum average monthly values of were −16.6 °C in January and 40.4 °C in July, respectively. Annual mean precipitation is 1072 mm, with peak values occurring from June to August. The soil, which was developed from alluvial deposits of the Yangtze River, is categorized as Cambisols according to World Reference Base of the International Union of Soil Sciences [37] and has a clayey texture. Detailed characteristics of the soil are listed in Table 1.

Undisturbed soil monoliths (50 cm in diameter × 70 cm in length) were collected using a cylindrical metal lysimeter drum (0.14 m^3) pushed with an excavator into the soil. A 10 cm opening was maintained between the casing top and the soil surface. The soil columns were then gently cut at the base of the surrounding soil and gradually lifted out of the collection site. A drum-like soil (20 cm in diameter and 5 cm deep) was then carved below the lysimeter drum, packed with clean white pebbles (1–2 cm in diameter), and enclosed with a nylon mesh within the lysimeter. A stainless-steel base plate with a drainage opening of 9.5 mm in diameter was then placed in the bottom of the lysimeter casing. The covering case at the base of the lysimeter was sealed with heat-resistant silicone sealant and then tightened with a gorilla grip after drying. Liquefied petroleum jelly (Vaseline) was inserted in the space made by the side of the lysimeter casing and the soil core to avoid preferential edge-flow [23]. The lysimeters were then carefully transported using the excavator and gently installed in an outdoor field framework close to the surface of the nearby soil. The space surrounding the lysimeter was then backfilled with soil to the same depth as the surface of the lysimeter. A plastic tube was installed in the drainage opening of the lysimeter base plate and connected to a well-rinsed plastic 10 L container to collect leachates (Fig. 1).

2.2. Experimental design

The lysimeter experiment was performed from November 2018 to September 2019, with the following seven treatments: no N fertilizer (Control); synthetic N fertilizer only at a conventional rate of 200/300 kg N ha^{-1} for wheat/maize (CN); 100/150 kg N ha^{-1} synthetic fertilizer plus 100/150 (DE1), 150/200 (DE2) and 250/350 (DE3) kg N ha^{-1} of dairy effluent; 100/150 kg N ha^{-1} synthetic fertilizer plus 100/150 kg N ha^{-1} dairy manure (SM1); and 150/225 kg N ha^{-1} synthetic fertilizer plus 50/75 kg N ha^{-1} dairy manure (SM2). Detailed information on the fertilizer treatments is presented in Table 2. The plots were placed in an entirely randomized design with four replicates each. Under CN and control treatment, potassium (potassium sulphate) and phosphorus (calcium superphosphate) were applied as basal fertilizer at rates of 100/112.5 kg K_2O ha^{-1} and 100/112.5 kg P_2O_5 ha^{-1} for wheat/maize, respectively. Under effluent and manure treatment, K and P were supplemented with potassium sulphate and calcium superphosphate. Basal fertilizers were applied uniformly by hand and promptly integrated into the soil to a 0–20 cm depth before sowing on November 11, 2018 for wheat and June 24, 2019 for maize. The dairy effluent and manure with moisture contents of 79.86 % and 36.54 %, respectively, were collected from Youran Dairy Farm Company Limited, which is in the neighbourhood of the experimental site. Detailed properties of the effluent and manure are presented in Table 1. Supplemental fertilizer urea was applied on March 4, 2019 and July 30, 2019 during the wheat and maize seasons, respectively (detailed rates are presented in Table 2). Maize (Yunmi 818) and wheat (Yannong 19) were seeded directly to a depth of 5 cm at rates of 7.5 plant m^{-2} and 45 g m^{-2}, and harvested at physiological maturity on November 11, 2018 and June 24, 2019, respectively. To determine aboveground biomass, the plants were dried for 3 days at 60 °C and weighed.

2.3. Collection and analysis of leachate

Ambient temperature and rainfall were measured using a meteorological instrument installed 2 m from the experimental site. Leachate was collected from the lysimeters 48 h after each precipitation event. Approximately 200 mL of leachate from each plot was used for laboratory analysis. After each leachate collection, clean containers were connected to the lysimeter. NO_3^- and NH_4^+ concentrations in the leachate were measured using a continuous flow auto-analyzer after filtration using Whatman No. 42 filter paper (Skalar San^{++} System, Breda, the Netherland). Remaining leachate from each plot was filtered using a 0.45 μm membrane to determine

Table 1
Properties of soil, effluent and manure.

	Depth	pH	BD	OC	TN	C/N	TP	TK	NH_4^+-N	NO_3^--N	Soil texture (%)		
	(cm)		(Mg m^{-3})	(g C kg^{-1})	(g N kg^{-1})		(g P kg^{-1})	(g K kg^{-1})	(mg N kg^{-1})	(mg N kg^{-1})	Silt	Clay	Sand
Soil	0–20	5.98	1.38	11.6	1.13	10.3	0.44	1.95	19.55	0.54	55.0	36.3	8.7
	20–40	6.25	1.85	9.75	0.66	14.8	0.65	1.19	–	–	57.5	35.3	7.2
	40–60	6.63	1.90	7.94	0.39	20.4	0.52	1.26	–	–	56.4	36.9	6.7
	60–80	6.70	1.96	6.70	0.33	20.3	0.57	1.36	–	–	56.0	35.7	8.3
Effluent	–	7.13	–	2.88	1.23	2.3	0.07	1.36	889	13.6	–	–	–
Manure	–	8.42	–	263	12.9	20.5	3.60	15.2	146	11.0	–	–	–

BD, soil bulk density; OC, organic carbon; TN, total nitrogen; TK, total potassium; TP, total phosphorus.

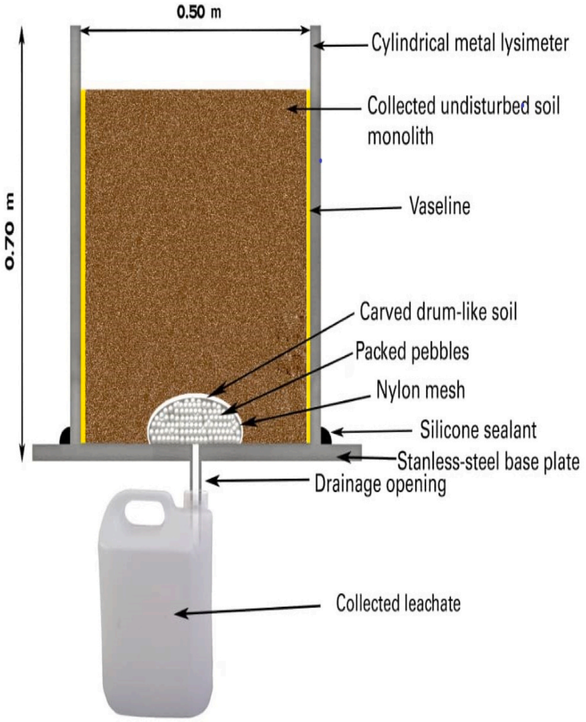

Fig. 1. Lysimeter construction.

Table 2
Application rates of synthetic N and organic N fertilizer.

Crop	Treatment	Total N (kg N ha^{-1})	Basal fertiliser (kg N ha^{-1})			Supplemental synthetic fertilizer (kg N ha^{-1})
			Synthetic fertilizer	Effluent	Manure	
Wheat	Control	0	0	0	0	0
	CN	200	100	0	0	100
	DE1	200	0	100	0	100
	DE2	250	0	150	0	100
	DE3	350	0	250	0	100
	SM1	200	0	0	100	100
	SM2	200	50	0	50	100
Maize	Control	0	0	0	0	0
	CN	300	150	0	0	150
	DE1	300	0	150	0	150
	DE2	350	0	200	0	150
	DE3	500	0	350	0	150
	SM1	300	0	0	150	150
	SM2	300	75	0	75	150

Control, no N fertilizer; CN, synthetic N fertilizer; DE1, dairy effluent rate 1; DE2, dairy effluent rate 2; DE3, dairy effluent rate 3; SM1, dairy manure 1; SM2, dairy manure 2.

the dissolved organic C (DOC) content using a TOC analyzer (Vario TOC Cube, Elementar, Germany). The amount of NH_4^+ and NO_3^- in the leachate was then calculated by multiplying the concentration in each leaching event by the total volume of drainage water collected. Values were expressed as kg N ha^{-1}.

The net ratio of inorganic N (NH_4^+ plus NO_3^-) leached to N applied (INLR, %) was then calculated using equation (1) as:

$$\mathrm{INLR} = \frac{\mathrm{L_F} - \mathrm{L_C}}{\mathrm{N_{rate}}} \times 100\% \tag{1}$$

where L_F and L_C denote the amount of inorganic N leaching (kg N ha^{-1}) under N fertilizer and Control treatment, respectively, and N_{rate} represents the rate of N applied (kg N ha^{-1}).

2.4. Estimations of N use efficiency

The N use efficiency (NUE, %) under each N application rate was calculated using the following formula [38,39] in equation (2):

$$\mathrm{NUE} = \left[\left(\mathrm{N_{fertilizer}} - \mathrm{N_{control}} \right) \Big/ \mathrm{N_{rate}} \right] \times 100 \tag{2}$$

where $N_{\mathrm{fertilizer}}$ and N_{control} denote nitrogen uptake in the aboveground biomass (kg N ha^{-1}) under N fertilizer and Control treatment, respectively, and N_{rate} represents the N application rate (kg N ha^{-1}).

2.5. Statistical analyses

All statistics were performed using SPSS 24.0 for Windows (SPSS Inc., Chicago, IL, USA). Before data analyses, the normality assumptions of residuals and constant variance (across the seven treatments) for analysis of variance (ANOVA) were determined. The total amount of rain during the experiment was calculated as the total water input. The effect of each treatment on the amount of leached water, NO_3^-, NH_4^+ and DOC leaching properties, and crop silage production were conducted using one-way ANOVA followed by Fisher's least significant difference test at $P < 0.05$ for multi-treatment comparisons.

3. Results

3.1. Precipitation, water leaching and soil temperature

Total precipitation was 350.6 mm during the wheat season, 54.6 % of which occurred from early December through late February, and 301.5 mm during the maize season, 56.6 % of which occurred from late June to July (Fig. 2). The annual value of 652.1 mm was considerably lower than the 30-year average value (1072 mm). Leaching in both seasons tended to occur following heavy precipitation events (>15 mm). During the wheat season, the highest rate of water leaching was 149.5 mm under Control treatment, which was significantly higher than that under all other treatments. Total water leaching during the maize growing season ranged from 62.5 to 84.8 mm under all treatments, and there were no appreciable variations in the treatments.

The highest evapotranspiration rate during the wheat season was 150.9 mm under DE1, while the lowest was 112.7 mm under Control treatment (Fig. 3). In contrast, the highest rate during the maize season was 179.9 mm under SM1, while the lowest was 157.6 mm under DE2. The air temperature varied from −3.4 to 30.5 °C during the wheat season, with an average of 10.0 °C, and from 19.9 to 35.6 °C during the maize season, with an average of 26.3 °C.

3.2. Concentrations of inorganic N and dissolved organic C in the leachate

A total of 13 and 4 leachate collections were carried out after heavy rainfall events in the wheat and maize seasons, respectively (Fig. 2). On some occasions during the wheat season, concentrations of NH_4^+-N, NO_3^--N and DOC in the leachate were significantly higher following effluent treatment than other treatments (Fig. 4a–f). Under CN treatment, NO_3^--N concentrations ranged from 9.77 to

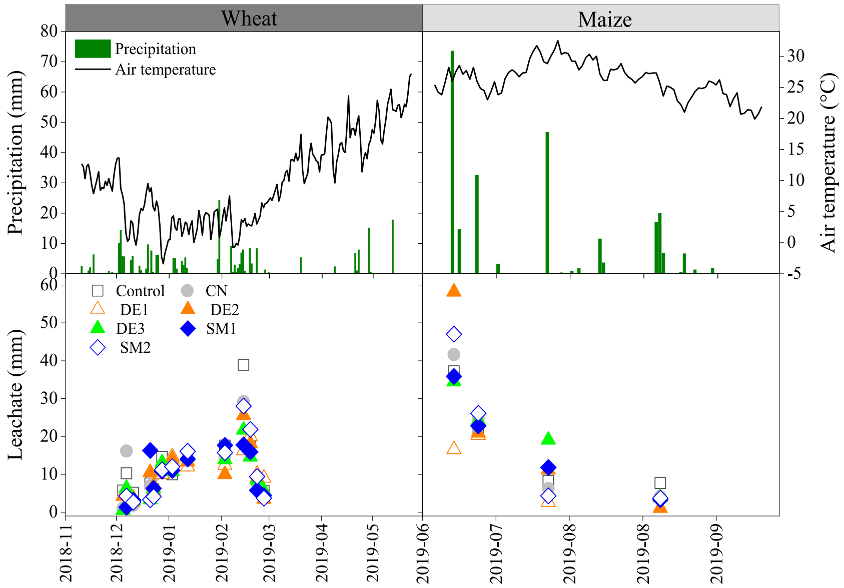

Fig. 2. Variations of air temperature, precipitation, and total leachate of different treatments. Vertical bars represent the SEMs (n = 4).

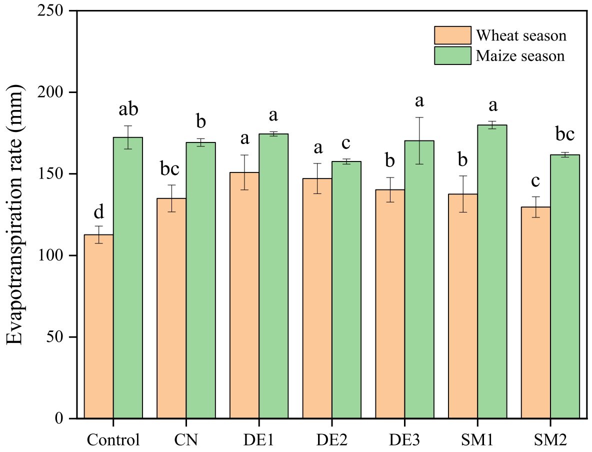

Fig. 3. Variations of total evapotranspiration in the treatments during the wheat and maize cropping. Vertical bars represent the SEMs (n = 4). Different letters indicate significant differences between treatments during the same season at $P < 0.05$.

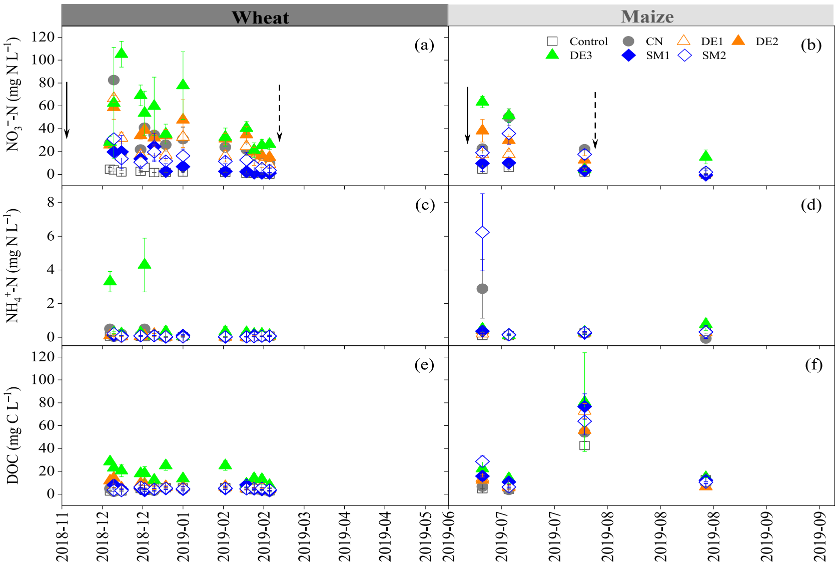

Fig. 4. Variations of nitrate (a, b), ammonium (c, d) and dissolved organic carbon (e, f) concentrations in leachate in the treatments during the wheat and maize cropping. The solid and dash arrows represent basal and supplemental fertilizer application times, respectively. Vertical bars represent the SEMs (n = 4).

82.48 mg N L^{-1}, with an average of 22.48 mg N L^{-1}. This was significantly higher than that under Control treatment, but statistically similar to that under DE1 (21.29 mg N L^{-1}) (Fig. 5a). Compared with DE1, mean NO$_3^-$-N concentrations increased by 40.7 % and 114.1 % under DE2 and DE3, respectively, compared to CN but decreased by 66.9 % and 51.4 under SM1 and SM2, respectively (Fig. 5c). The highest mean concentration of NH$_4^+$-N was 0.69 mg N L^{-1} under DE3, while under CN, the mean concentration was 0.07 mg N L^{-1}, and did not differ from that under Control, DE1, DE2, SM1 and SM2 (Fig. 5d–f). The highest mean DOC concentration was 17.03 mg C L^{-1} under DE3, followed by DE2 and DE1, while the lowest was 4.34 mg C L^{-1} under Control treatment (Fig. 5g). Overall, the DOC concentrations among the treatments did not differ significantly, except for that under DE3 (Fig. 5i).

During the maize season, the average NO$_3^-$-N concentration ranged from 1.99 to 50.63 mg N L^{-1} under CN, with an average of 28.92 mg N L^{-1}, which was significantly higher than that under Control and DE1 treatment (Fig. 5b). Meanwhile, under DE2 and DE3, NO$_3^-$-N concentrations increased by 43.7 % and 114.6 % compared with DE1, respectively, while under SM1 and SM2, concentrations decreased by 80.1 % and 28.5 % compared with CN, respectively. The average concentrations of NO$_3^-$-N in the leachate increased quadratically with the application rate of effluent N during both the wheat and maize seasons (Fig. 6 a, b). The highest mean concentration of NH$_4^+$-N was 1.57 mg N L^{-1} under SM2, followed by CN (0.68 mg N L^{-1}), DE3 (0.45 mg N L^{-1}), SM1 (0.24 mg N L^{-1}) and DE1 (0.16 mg N L^{-1}) (Fig. 5e). The average DOC concentration was 24.69 mg C L^{-1} under CN, which was significantly higher than that under Control treatment, but significantly lower than that under DE1. Overall, DOC concentrations decreased under DE2 and DE3

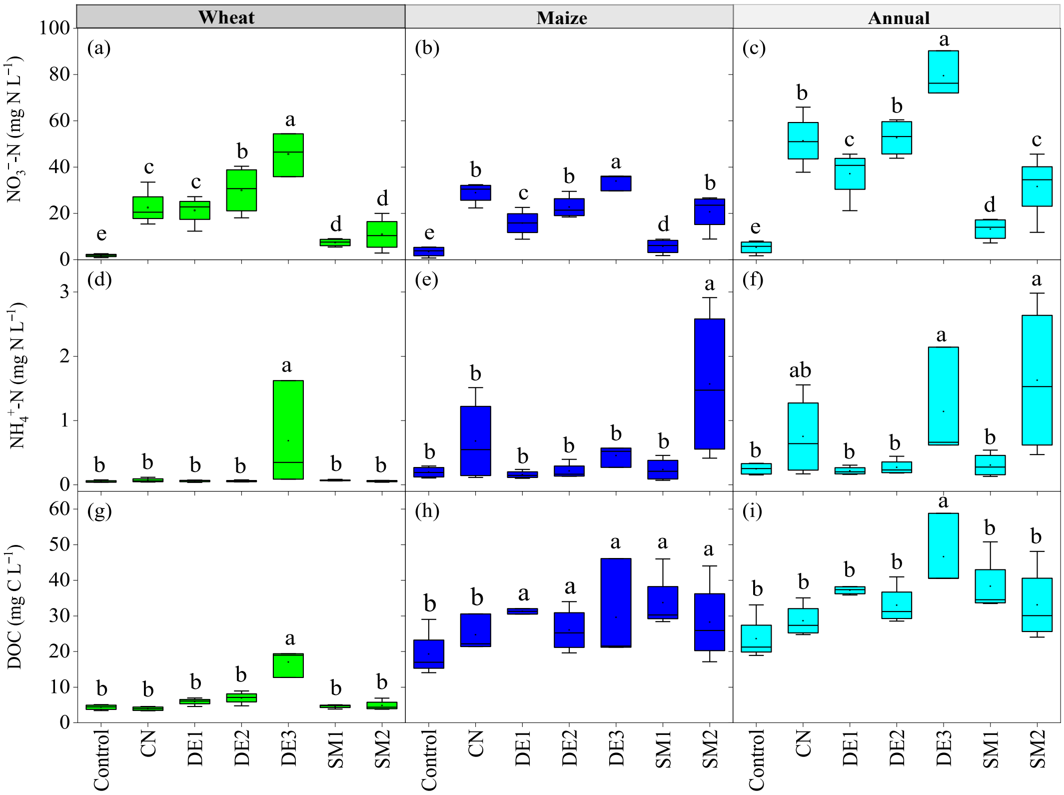

Fig. 5. Seasonal and annual mean concentrations of nitrate (a, b, c), ammonium (d, e, f) and dissolved organic carbon (g, h, i) in leachates in the treatments during the wheat and maize cropping year. Different letters indicate significant differences between treatments at $P < 0.05$.

compared to DE1 (Fig. 5h), while increases of 34.2 % and 43.8 % were observed under SM1 and SM2 compared to CN, respectively.

3.3. *Leaching losses of inorganic N*

Throughout the wheat cropping, 27.68 kg N ha^{-1} inorganic N (NH_4^+-N plus NO_3^--N) was leached under CN, which was significantly higher than that under Control and DE1 treatments by 1048.3 % and 28.8 %, respectively (Fig. 7a). Compared with CN, leaching of inorganic N increased significantly by 27.2 % and 82.0 % under DE2 and DE3, but decreased by 74.3 % and 42.9 % under SM1 and SM2, respectively ($P < 0.05$).

NO_3^--N accounted for 97–99 % of the total inorganic N leached under all treatments. Total leaching of NO_3^--N was 21.43 kg N ha^{-1} under DE1 treatment, lower than that under CN treatment, while 35.16 and 49.91 kg N ha^{-1} were leached under DE2 and DE3, respectively. In contrast, total leaching of NO_3^--N decreased significantly by 74.4 % and 42.9 % under SM1 and SM2 compared with CN, respectively ($P < 0.05$). There was a strong association between NO_3^--N leaching losses and the effluent N application rate ($P < 0.05$, Fig. 6 c, d). During the wheat cropping, the ratio of N leached to N applied was 12.64 % under CN treatment, and decreased significantly by 24.5 %, 81.3 % and 48.7 % under DE1, SM1 and SM2, respectively ($P < 0.05$). In contrast, a 3.8 % and 7.4 % increase was observed under DE2 and DE3, respectively (Fig. 7c).

During the maize cropping, the greatest loss from N leaching loss was 33.8 kg N ha^{-1} under DE3, followed by DE2 (Fig. 7b). In contrast, N leaching was 9.89 kg N ha^{-1} under CN, considerably higher than that in DE1 and SM1 by 67.9 % and 166.9 %, respectively, but similar to that under SM2 ($P < 0.05$). NO_3^--N accounted for 94–99 % of the total N leached under all treatments. The ratio of N leached to the applied N was 2.65 % under CN, but decreased to 1.31 % under DE1 and increased to 4.46 % and 6.28 % under DE2 and DE3, respectively (Fig. 7d). Meanwhile, compared with CN, a significant decrease of 77.9 % was observed under SM1 treatment.

Overall, inorganic N leaching losses were higher in the wheat cropping than in the maize cropping. Annual inorganic N leaching was significantly higher under CN (37.58 kg N ha^{-1}) than under Control and DE1 treatment, but lower than that under DE2 and DE3 by 40.5 % and 123.9 %, respectively ($P < 0.05$). Meanwhile, N leaching decreased by 71.2 % and 32.0 % under SM1 and SM2 treatment, respectively.

3.4. *Silage yield and NUE*

Wheat aboveground biomass was identical under CN and DE1 treatment at 10.60 Mg ha^{-1}, which was significantly higher than that

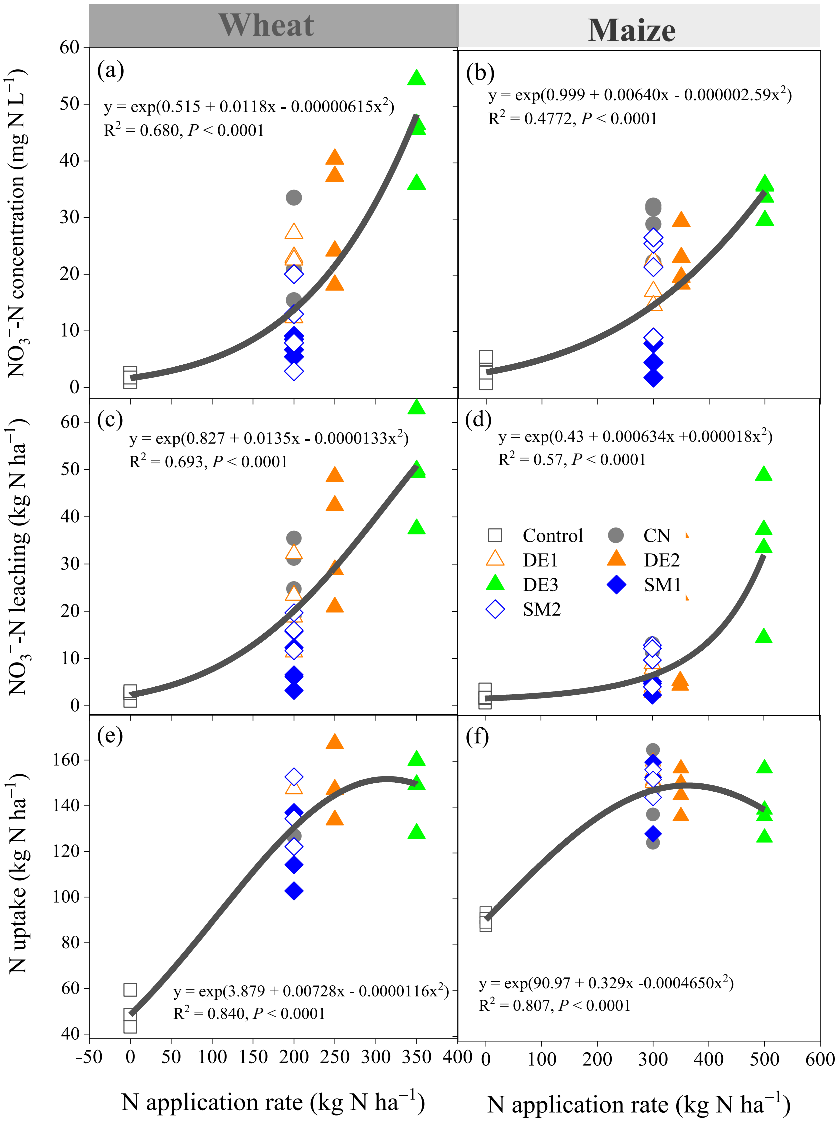

Fig. 6. Correlations between mean leachate nitrate concentration (a, b), total nitrate leaching losses (c, d), or N uptake (e, f) and the N application rate during the wheat and maize cropping.

under Control and SM1 treatment, but lower than that under SM2 ($P < 0.05$). In comparison to CN, a significant increase in wheat silage of 16.7 % was observed under DE3 treatment ($P < 0.05$), while an increase of 8.8 % was observed under DE2, albeit not significantly. There was a quadratic correlation between aboveground biomass and the N application rate in all treatments and a similar relation between aboveground biomass and the N application rate in all but excluding the two dairy manure treatments (Fig. 8). N uptake was 126.7 kg N ha^{-1} under CN, which was substantially higher than that under Control treatment ($P < 0.05$), but lower than under SM2 and all effluent treatments. The highest N uptake was observed under DE3 at 149.2 kg N ha^{-1}, but this was not considerably different from that under DE2 and DE1 (Table 3). The highest NUE during the wheat season was 49.4 % under DE1, with 21.6 % and 41.8 % decreases under DE2 and DE3 treatments, respectively. Meanwhile, under SM2, the NUE was 42.1 %, which was significantly higher than that under CN ($P < 0.05$).

Maize silage yield was 13.26 Mg ha^{-1} under CN, with a significant increase of 10.0 % under DE1. Compared with CN, there were no significant differences in yield under DE3 and SM2, although a decrease of 10.0 % was observed under DE2 and SM1 (Table 3). Highest N uptake during the maize season was 154.3 kg N ha^{-1} under DE1 compared to 143.3 kg N ha^{-1} under CN, with a slight increase of 2.1 % and 4.1 % under SM1 and SM2, respectively. The highest NUE during the maize season was 21.8 % under CN, which was substantially higher than that under DE2 and DE3 by 16.1 % and 9.75 % ($P < 0.05$), respectively, but similar to that under DE1, SM1 and SM2.

N uptake reached a maximum of 300 kg N ha^{-1} in both the wheat and maize cropping seasons, with a maximum silage yield of 300 kg N ha^{-1} for maize and 350 kg N ha^{-1} for wheat (Fig. 6 e, f). Overall, the annual average NUE was inversely associated to N leaching

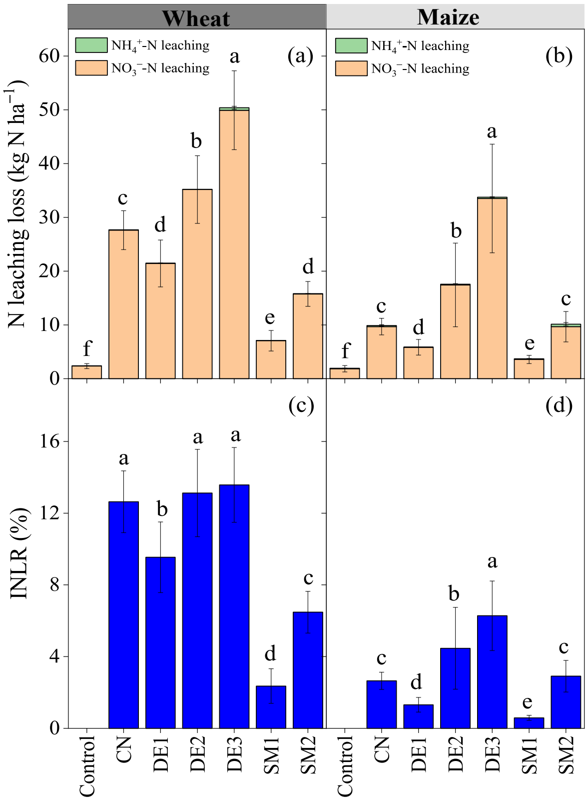

Fig. 7. Magnitude of nitrate and ammonium leaching loss (a), and ratio (INLR%) of leaching N in leachates to the N applied (b) in the treatments during the wheat and maize cropping. Different letters indicate significant differences between treatments at $P < 0.05$.

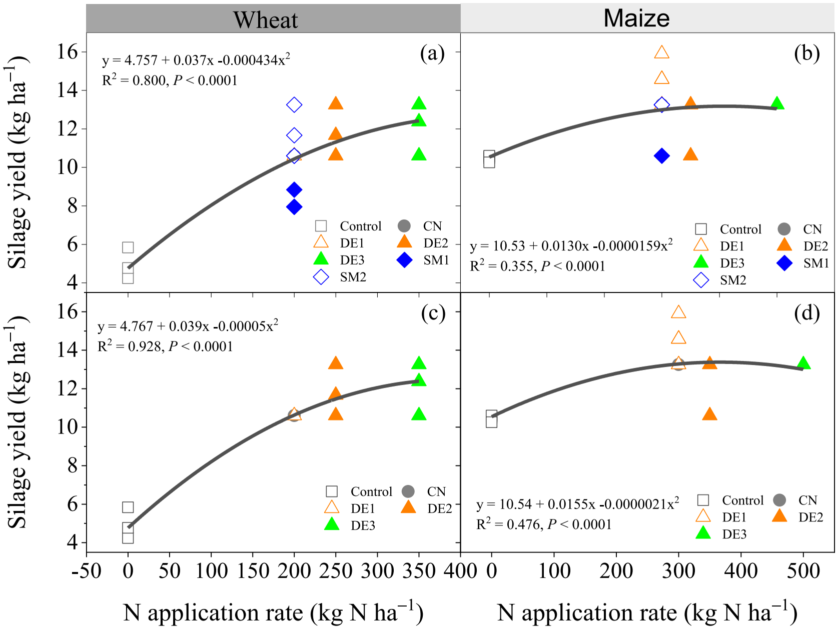

Fig. 8. Correlations between total silage yield and the N application rate in all treatments (a, b) and all but excluding manure treatments (c, d) during the wheat and maize cropping.

Table 3
Silage yield, N uptake in aboveground biomass and nitrogen use efficiency (NUE) as affected by dairy effluent and manure during the wheat and maize season.

Crop	Treatments	Silage yield (Mg ha^{-1})	N uptake (kg N ha^{-1})	NUE (%)
Wheat	Control	4.77 ± 0.53d	48.54 ± 3.81d	–
	CN	10.60 ± 0.00b	126.67 ± 0.21c	39.06 ± 1.19b
	DE1	10.60 ± 0.00b	147.38 ± 0.15a	49.42 ± 1.19a
	DE2	11.53 ± 0.63b	145.45 ± 7.90a	38.76 ± 4.36b
	DE3	12.37 ± 0.62a	149.18 ± 7.53a	28.75 ± 2.72c
	SM1	8.84 ± 0.62c	114.13 ± 8.07c	32.79 ± 4.74c
	SM2	11.53 ± 0.63b	132.74 ± 7.21b	42.10 ± 5.12a
Maize	Control	10.47 ± 0.08c	90.87 ± 1.27c	–
	CN	13.26 ± 0.00a	143.28 ± 8.56a	21.77 ± 2.67a
	DE1	14.58 ± 1.33a	154.33 ± 2.11a	21.15 ± 0.80a
	DE2	11.93 ± 0.77b	147.14 ± 4.42a	16.08 ± 1.48b
	DE3	13.26 ± 1.33a	139.60 ± 6.31b	9.75 ± 1.26c
	SM1	11.93 ± 0.77b	146.31 ± 6.75a	20.17 ± 1.06a
	SM2	13.26 ± 0.00a	149.21 ± 3.01a	21.20 ± 0.39a

Means ± standard errors (n = 4). Values followed by different letters within the same column indicate significant differences between treatments at $P < 0.05$.

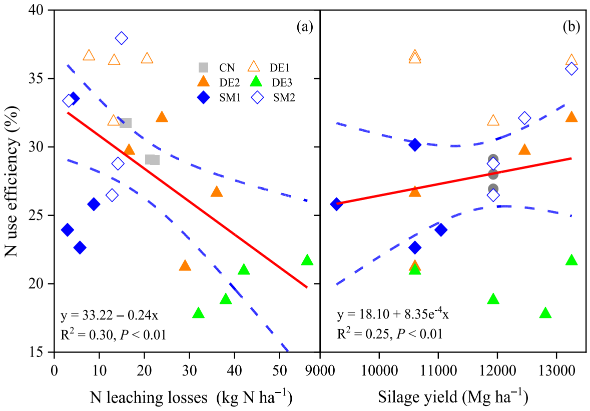

Fig. 9. Correlation between annual mean N use efficiency (NUE) and annual mineral N leaching losses (a) and annual silage yield (b) in the wheat and maize cropping system. The dashed lines indicate the 95 % confidence interval of the regression line.

and positively correlated with annual silage yield (Fig. 9 a, b).

4. Discussion

4.1. Annual N leaching intensity with synthetic N fertilizer

Under CN, the annual N leaching losses and ratio of N leached to N applied were 37.6 kg N ha^{-1} and 15.3 %, respectively. This is lower than values reported previously (47.0–55.7 kg N ha^{-1} and 16.2–21.2 %, respectively) in wheat-maize cropping under rates of N application of 550–600 kg N ha^{-1} [40,41]. N leaching is a water-controlled process, with excessive water input causing the downward movement of N [42] and heavy precipitation representing the direct cause of N leaching in croplands [14]. Huang et al. [1] reported N leaching losses of 46.4 kg N ha^{-1}, with a dramatic increase to 60.2 kg N ha^{-1} with increases in precipitation from 859 to 927 mm under an application rate of 478–560 kg N ha^{-1}. This is considerably higher than the values of 15.0–38.4 kg N ha^{-1} observed under precipitation of between 544.4 and 680.3 mm at N application rates of 480–520 kg N ha^{-1} [43,44]. In this study, it is likely that the relatively low N leaching ratio is thought to have been related to the low annual rainfall of only 652.1 mm.

Wang et al. [45] suggested that soil texture affects water infiltration and nutrient leaching losses, while Frick et al. [22] concluded that N leaching losses in loamy sand/silt soil are more severe than in clay loamy soil, due to the lower retention rate and higher conductivity [46]. In addition, NH_4^+ is readily adsorbed by internal clay surfaces [47], and soil containing 36.0–40.3 % clay minerals was found to adsorb 50–300 mg N kg^{-1} in the form of NH_4^+ [48]. In this study, clay minerals accounted for 36.3 % of the soil layer at depth 0–20 cm, suggesting that NH_4^+ was effectively adsorbed and retained. Therefore, another possibility is that reducing NH_4^+ availability for nitrification and NO_3^--N production due to high adsorption by rich clay content in test soil reduces NO_3^--N leaching losses.

4.2. Effect of effluent application rates on annual N leaching

Previous studies indicate that the application of effluents stimulates NO_3^--N leaching losses compared with synthetic N fertilizer applied at the same rate of 200–800 kg N ha^{-1} [19,24]. Out of expectation, in this study, a reduction in N leaching losses of 27.1 % was observed under DE1 during the wheat – maize cropping year compared with CN treatment. Similarly, Bakhsh et al. [49] and Du et al. [19] reported a reduction in N leaching of 20.0–34.6 % following the combined application of 50 % dairy slurry N plus 50 % urea N compared with urea application alone at a rate of 160–192 kg N ha^{-1}. Salazar et al. [50] even recorded low N leaching losses (1.2–1.4 kg N ha^{-1}) immediately after applying 400 kg N ha^{-1} effluent. Several possible reasons exist for the reduction in N leaching losses under DE1. Firstly, although urea, the major constituent of effluent, is readily hydrolyzed to NH_4^+ and rapidly nitrified into NO_3^--N [39], more than 36 % of organic N in effluent is slowly mineralized, thereby lowering the availability of inorganic N for leaching [51]. Secondly, the increase in N uptake and NUE under DE1 compared to CN treatment will further reduce the availability of inorganic N for leaching [8]. Thirdly, labile organic C within the effluent stimulates microbial immobilization of inorganic N in the soil, especially the subsoil, thus reducing substrate availability for nitrifiers and NO_3^- production [18]. Fourthly, rich oxidizable soluble C within the effluent accelerates the formation of anaerobic microsites for denitrification, thereby enhancing the conversion of NO_3^- to N_2O and N_2 [52]. Finally, the annual volume of leached water under DE1 treatment was 10.6 % lower than that under CN, primarily due to the higher evapotranspiration rate resulting from the increase in crop biomass (Fig. 3), which in turn will have reduced deep soil N leaching [22].

In contrast, sharp increases in N leaching losses were observed under DE2 and DE3 treatment compared with CN, and there was an exponential correlation between N leaching losses and the effluent N application rate, as reported previously [53]. Excessive effluent application was previously found to enhance the availability of NH_4^+ for nitrification due to direct input as well as the mineralization of effluent organic N, thereby increasing the soil NO_3^- pool [54]. The threshold NO_3^- concentration for the occurrence of leaching was previously estimated at 25–36 and 15–21 mg N kg^{-1} in wheat and maize rhizosphere soil, respectively [55,56]. In this study, the concentration of soil NO_3^- under DE2 and DE3 treatment was 1.3–1.9 times greater than these threshold values. Lu et al. [10] reported that NO_3^- accumulation in the soil occurred when the fertilizer N rate reached 143 and 168 kg N ha^{-1} for wheat and maize, respectively. When the annual application rate of fertilizer N plus effluent N increased from 180 to 350 to 550–750 kg N ha^{-1} under wheat-maize cropping, a reduction in NUE of 16–49 % was reported, with an annual accumulation of inorganic N below the roots and vadose zones of 45–168 kg N ha^{-1} [10,19]. Bakhsh et al. [49] and Barkle et al. [57] concluded that high rates of N application at 345–601 kg N ha^{-1} resulted in persistent effluent organic N mineralization, with continuous release of clay-fixed N during the growing season, which in turn increased N accumulation below the root zone, resulting in more significant N leaching losses.

4.3. Effect of effluent application on seasonal N leaching

Surprisingly, 61.3–78.2 % of the annual N leaching losses occurred during the wheat season, similar to the finding of Yang et al. [53] but differing from Long et al. [58]. Overall, N uptake by maize was slightly higher than that by wheat, which might partly, but not completely, account for the lower rate of N leaching during the maize season. Ammonia volatilization was previously found to cause low NO_3^- leaching losses in dry seasons following effluent application [59]. Our field measurements suggest that the ratio of NH_3 loss to N applied was considerably higher during the maize season than the wheat season [60]. This is thought to have been the result of various factors. Firstly, higher air temperatures accelerate the mineralization of organic N in effluent [61], increasing the concentration of topsoil NH_4^+. Secondly, higher rates of effluent application elevate soil salinity, which is thought to inhibit the activity of nitrifiers, thereby suppressing the oxidation of NH_4^+ to NO_3^- [62]. Thirdly, effluent-induced increases in soil pH coupled with high temperatures facilitate the volatilization of NH_3 [63].

In contrast, Huang et al. [1] argued that the NO_3^--N movement from the root zone primarily depends on soil water flow, occurring when water input from precipitation and irrigation is higher than the evapotranspiration rate [64]. It was also revealed that when the volume of leachate increased from 4 to 13 mm, NO_3^--N leaching losses increased sharply from 0.9 to 13.3 kg N ha^{-1} during the wheat season [43]. In this study, the wheat season saw more precipitation than maize season did, as was the higher volume of leachate, suggesting that the low precipitation rate reduced losses from N leaching during the maize season. In line with this, Malcolm et al. (2016) revealed an increase in NO_3^- leaching losses during the summer compared to the winter, because effluent application coincided with abundant precipitation and higher air temperatures [65]. Our findings suggest, therefore, that high basal application of effluent combined with low crop N requirements during the early stage of growth resulted in redundant NO_3^- and increased N leaching risk during the wheat season.

4.4. Effect of manure application on N leaching

Previous research indicates that the application of organic manure with synthetic N fertilizer at rates of 120–400 kg N ha^{-1} increased N leaching to 35.5–45.2 kg N ha^{-1} than with 10.1–33.2 kg N ha^{-1} under synthetic N fertilizer application alone at rates of 180–408 kg N ha^{-1} [66,67]. In contrast, in this study, annual N leaching losses under SM1 and SM2 treatments were significantly lower than that under CN treatment. Three potential reasons are suggested for the reduction in N leaching losses under manure treatment. Firstly, compared with SM2, SM1 treatment showed significantly lower annual N leaching. Aronsson et al. [68] and Yang et al. [69] reported that a higher ratio of dairy and swine manure N to urea N lowered NO_3^--N concentrations in the groundwater by 27–197 %, since manure reduced inorganic N release and subsequent NO_3^--N production in comparison to urea alone. Thus, lower NO_3^- leaching loss under manure treatment was at least due to a relatively high ratio of manure N to urea N, which efficiently reduced inorganic N release and soil N availability for nitrifiers. Secondly, the high ratio of C/N in the test manure lowered the mineralization rate of organic N [70], thereby reducing soil inorganic N availability and NO_3^--N. Thirdly, manure treatments (SM1 and SM2) compared with CN reduced the volume of leached water, albeit not significantly. This is because the addition of manure increases soil water and nutrient storage capacity by lowering soil bulk density, improving soil structure, and even accelerating the formation of aggregates [71]. Du et al. [19] reported that the reduction in soil bulk density following manure amendment lowers soil water penetration, thereby reducing N leaching [72,73]. However, a decrease in silage yield was also observed under SM1 treatment. Together, these findings indicate that substituting 25 % conventional synthetic N fertilizer with dairy manure could mitigate N leaching.

4.5. Management of dairy farm effluent and manure application

To maximize silage yield, farmers tend to apply excessive synthetic and organic fertilizers, resulting in substantial NO_3^- accumulation within soil and subsequent N losses through runoff or leaching, all of which pose environmental risks [74]. In this study, annual N leaching losses were significantly lower under SM1, SM2 and DE1 compared to CN treatment ($P < 0.05$). Moreover, DE1 and SM2 treatments recorded higher silage yield and NUE during the wheat season, and a higher yield and N uptake during the maize season compared with CN, suggesting that the application rates of effluent under DE1 and manure under SM2 resulted in highest agronomic values [9]. These findings suggest that the rates of application under DE1 and SM2 were optimally synchronized with crop nutrient requirements [75]. In contrast, a reduction in silage yield and NUE were observed under SM1 compared with CN due to the insufficient release of inorganic N during manure decomposition [76,77].

Surprisingly, only N uptake rather than silage yield was improved during the wheat season under DE2 treatment. According to earlier research, N application rates greater than 200–300 kg N ha^{-1} could increase N accumulation in crops, but not yield under wheat-maize cropping [13]. The optimal N application rates were earlier proposed to range from 162 to 250 kg N ha^{-1} for both wheat and maize [35,40]. However, our results suggest that replacing 25 % synthetic N fertilizer with dairy manure N and 50 % synthetic N fertilizer with effluent N at 200 kg N ha^{-1} for wheat and 300 kg N ha^{-1} for maize were beneficial in terms of mitigating N leaching losses and increasing silage yield (Fig. 8a–d). It should be mentioned that the current study highlights the short-term benefits of DE1 and SM2 treatments for reducing N leaching and increasing crop productivity in the wheat-maize cropping system, it overlooks the long–term consequences. Our subsequent study will focus on the long-term effect of substituting synthetic N fertilizer on greenhouse gas emissions, ammonia volatilization and crop productivity.

5. Conclusions

The findings of this study imply that replacing 50 % synthetic N fertilizer with effluent (DE1) increased maize yield by 10.0 %, wheat NUE by 26.5 %, and N uptake in both wheat and maize by 7.7–16.3 %, while reducing N leaching losses by 22.4 % and 40.4 % in the wheat and maize seasons, respectively, compared with CN. In contrast, further increases in effluent application rates significantly increased N leaching losses by 27.2–241 % and reduced NUE by 26.2–55.2 %. Meanwhile, replacing 25 % synthetic N fertilizer with manure N (SM2) also increased yield by 8.8 % and NUE by 7.8 %, and reduced N leaching losses by 42.9 % during the wheat season. Annual N leaching under CN treatment was 37.6 kg N ha^{-1}, with 27.1 % and 32.0 % reductions under DE1 and SM2, respectively, while increased by 40.5–123.9 % under DE2 and DE3. Overall, these results suggest that substituting 25 % synthetic N with manure N and 50 % synthetic N with effluent N offers an eco-friendly strategy for the management of wheat-maize cropping systems in terms of N leaching losses and crop productivity.

Availability of data and materials

Data associated with the study has not been deposited into a publicly available repository and is available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Obemah David Nartey: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Deyan Liu:** Validation, Supervision, Conceptualization. **Jiafa Luo:** Writing – review & editing, Validation. **Stuart Lindsey:** Writing – review & editing, Validation. **Zengming Chen:** Writing – review & editing, Validation. **Junji Yuan:** Writing – review & editing, Validation. **Mohammad Zaman:** Writing – review & editing. **Jonathan Nartey Hogarh:** Writing – review & editing. **Weixin Ding:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests: Weixin Ding reports on the independent innovation fund of Agricultural, Science and Technology in Jiangsu Province (SCX (20)1013), and IAEA coordinated research project (D15020), Liu Deyan reports on the Jiangsu Agriculture Science and Technology Innovation Fund (JASTIF) (Grant No. CX(21) 2018), Obemah David Nartey reports on the storage and application effect of dairy effluents on greenhouse gas and ammonia emissions, and nutrient leaching in upland fields in Luhe, Jiangsu Province, China under the

Ph.D Joint President's Fellowship by the World Academy of Sciences and Chinese Academy of Sciences (CAS-TWAS). If there are other authors, they declare that any known competing financial interests or personal relationships could have influenced none of the works reported in this study.

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