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An assessment of urea-based fertilisers for reducing nutrient leaching from contrasting soils under wheat crops

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ABSTRACT

This study assessed the effects of different urea-based fertilisers on nutrient leaching, wheat yield and nitrogen (N) use efficiency (NUE) in two clayey, alkaline soils from Morocco and two sandy, acidic soils from Nigeria. The study was carried out in a controlled environment room under optimum conditions. Columns of the soils were sown with spring wheat, treated with different urea-based fertilisers applied basally and on the soil surface, and leached four times with a dilute salt solution. In the soil with the highest soil N supply, all of the fertilisers increased N leaching compared to when no fertilisers were applied. Furthermore, including inhibitors with urea or having urea in a slow-release format did not affect N leaching compared to when N was applied as straight urea. In soils with lower soil N supply, applying straight urea did not affect N leaching compared to the control with no N applied. However, including a urease inhibitor with urea caused an increase in N leaching. The inhibitor may have allowed the urea to penetrate deeper into the soil before being hydrolysed, decreasing ammonia (NH_3) volatilisation losses from the soil surface and increasing the concentration of mobile N below the root zone available for leaching. Including a nitrification inhibitor with the urease inhibitor or having urea in slow-release format brought N leaching back down to background levels. Although yields were similar, the dual inhibitor proved better for maintaining NUE than the slow-release fertiliser in two of the four soils. Therefore, urea with a urease and nitrification inhibitor is the reccomended fertiliser for reducing N losses via leaching while simultaneously maintaining NUE. However, the extent of these changes are likely to vary depending on experimental conditions such as seeding rates, fertiliser rates, method of application and experimental set-up.

1. Introduction

Urea is the most widely used form of nitrogen (N) fertiliser globally, accounting for approximately 50% of N fertiliser use (International Fertilizer Association, 2022). This is due to its high N content and low economic cost. However, surface applications of urea can lead to ammonia (NH_3) losses via volatilisation, with consequences for air quality, water quality and N sensitive habitats following NH_3 deposition (Guthrie et al., 2018). In addition, excess rainfall or irrigation water can leach N from fertilisers into drainage waters, contaminating waterbodies and degrading water quality and aquatic habitats (Cassman & Dobermann, 2022; Glibert et al., 2006). These environmental losses reduce the amount of N that is available to crops and therefore represent both an environmental concern and an economic loss for farmers (Carswell et al., 2019; Kang et al., 2023).

The impacts of NH_3 and other air pollutants have driven international commitments to reduce air pollution, such as the Gothenberg Protocol, which requires member states to lower NH_3 emissions from solid urea-based fertilisers (2012 amendment to Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone Gothenburg, 1999). One effective strategy to mitigate NH_3 losses from urea fertilisers is the use of urease inhibitors. These inhibitors slow the hydrolysis of

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urea into ammonium (NH_4^+), delaying peak NH_3 volatilisation and thereby reducing overall emissions (Byrne et al., 2020). A large body of evidence supports the effectiveness of urease inhibitors in reducing NH_3 emissions (Matse et al., 2024; Quan et al., 2021). However, there is no equivalent body of evidence for the effects of urease inhibitors on N leaching losses (Cai & Akiyama, 2017; Wang et al., 2025). Consequently, the implications of incorporating urease inhibitors into urea fertilisers for N leaching remain unclear.

The studies that have examined the effects of urease inhibitors on N leaching losses do have limitations. They have not always measured all forms of N, included plants in the system, considered impacts on other nutrients, or accounted for variations across contrasting soils (e.g. Dawar et al., 2011; de Paulo et al., 2021; Gioacchini et al., 2002; Kibet et al., 2016; Sanz-Cobena et al., 2012). The results have also been varied with some studies observing reductions in nitrate (NO_3^-) leaching when urease inhibitors are used with urea fertilisers (Dawar et al., 2011; Sanz-Cobena et al., 2012) and other studies observing increases (Gioacchini et al., 2002; Kibet et al., 2016). However, the reduced NH_3 volatilisation associated with inhibitor use has consistently led to a greater amount of NH_4^+ in the soil (Drame et al., 2023; Kirschke et al., 2019; Wang et al., 2024), which could be available for nitrification and subsequent NO_3^- leaching. Such NO_3^- leaching losses from urea fertilisers could be mitigated by the use of nitrification inhibitors. These inhibitors slow the initial step of the nitrification process, the oxidation of NH_4^+ to NO_3^-, thereby reducing NO_3^- leaching (Byrne et al., 2020). This could also improve nitrogen use efficiency (NUE), i.e., the proportion of applied N fertiliser that ends up in the crop (Dobermann, 2005; Quan et al., 2021), which should be a key consideration for selecting fertilisers. A combined approach using both urease and nitrification inhibitors could, therefore, be an option to achieve the aim to simultaneously reduce NH_3 emission, reduce N leaching and improve NUE (de Paulo et al., 2021; Guertal & Howe, 2012). Another option for this aim could be the use of slow-release fertiliser technology. These fertilisers are coated to physically control the release of N from granules. By slowing the release of N, they help reduce peak emissions and extend the period during which the crop can take up the N (Guertal & Howe, 2012; Liu et al., 2023; Yang et al., 2021).

Promising fertilisers should be tested across a range of contrasting soils since their efficiency for reducing NH_3 emissions and improving NUE will vary with soil properties, which may have knock-on impacts on N leaching. Meta-analyses provide useful information on fertiliser efficiency across soil types. For instance, across a wide range of studies, Wang et al. (2024) found that urea fertilisers with urease and nitrification inhibitors had a greater effect in lowering NH_3 emissions in acid soils than in alkaline soils. In a similar analysis, Abalos et al. (2014) linked greater crop yield and NUE when inhibitors are applied with fertilisers in acid soils to the inherently lower NH_3 emissions from acid soils. They suggest that the increased soil NH_4^+ related to nitrification inhibitor use was less susceptible to NH_3 volatilisation in acid soils than in alkaline soils. In another *meta*-analysis, Wang et al. (2025) found that inhibitors reduced NO_3^- leaching to a greater extent in soils with a pH below 8, due to better nitrification inhibitor efficiency. However, there weren't enough studies to be able to differentiate between the different inhibitors or effects on different N forms, which further highlights the need for greater understanding in this area.

The aim of this study was therefore to assess the efficiency of a range of different urea-based fertilisers for reducing nutrient leaching from contrasting soils from Mediterranean and sub-Saharan Africa. We hypothesise increased N leaching under crops fertilised with urea and a urease inhibitor, which can be reduced by the addition of a nitrification inhibitor or with the use of slow-release technology. Additionally, this reduction of N leaching would be greater in soils of lower pH due to better nitrification inhibitor efficiency. The focus was on soils from Mediterranean and sub-Saharan Africa, where N removal via crops often exceeds fertiliser inputs, leading to soil N mining (Ludemann et al., 2024). These areas represent some of the few parts of the World where N inputs to cropping systems can and should be increased without exceeding critical surplus levels (Cassman & Dobermann, 2022). Ideally this would be done sustainably, with the use of inhibitors for example, to avoid the problems of air and water pollution that have resulted from fertiliser use in countries with surplus N.

2. Materials and methods

2.1. Soil sampling and characterisation

Soils were sampled to a maximum depth of 20 cm using a triangular-shaped sampling strategy at two locations in Morocco and Nigeria. The Moroccan sampling sites included Beni Mellal in the Beni Mellal-Khenifra region (32°20′25.0″N, 6°22′45.0″W) and Meknes situated in the Fez-Meknes Region (33°53′16.0″N, 5°36′17.9″W). The Nigerian sites were Ibadan in Oyo State (7°25′59.0″N 3°53′10.1″E) and Ikenne in Ogun State (6°50′55.0″N 3°41′57.9″E). These soils contrasted in inherent properties important for N cycling: two of them were clayey and alkaline, and two were sandy and acidic (Table 1). Additionally, the Ibadan soil had the highest soil N supply as evidenced by summing soluble NH_4^+, total oxidisable N (TON) and Organic N (Table 1). The soils were air-dried, sieved through 2 mm mesh, thoroughly mixed and then analysed for basic properties (Table 1).

Table 1

Mean and standard error ($n = 3$) of physicochemical properties of the four experimental soils. Abbreviations: TON, total oxidisable N; DWE, dry weight equivalent; BLD, below limit of detection.

	Units	Beni Mellal (Morrocco)	Ibadan (Nigeria)	Ikenne (Nigeria)	Meknes (Morrocco)
Sand	%	23.4 ± 5.2	54.8 ± 0.9	60.7 ± 5.2	13.2 ± 2.0
Silt	%	43.8 ± 6.7	26.8 ± 0.6	13.0 ± 0.4	36.6 ± 0.4
Clay	%	32.8 ± 2.6	18.4 ± 1.1	26.3 ± 4.9	48.2 ± 0.3
Textural class (ADAS)	NA	Clay	Sandy loam	Sandy clay loam	Clay
pH in H_2O	pH units	7.97 ± 0.06	5.85 ± 0.01	5.46 ± 0.003	8.18 ± 0.01
pH in $CaCl_2$	pH units	7.63 ± 0.01	4.82 ± 0.01	5.18 ± 0.02	7.70 ± 0.01
Organic matter	%	4.49 ± 0.39	4.13 ± 0.25	1.84 ± 0.02	3.16 ± 0.04
Water holding capacity	% soil moisture	30.9 ± 0.4	31.1 ± 0.3	20.9 ± 0.3	33.2 ± 0.4
Total C	g kg^{-1} DWE	23.3 ± 0.3	13.6 ± 0.2	7.7 ± 0.1	43.1 ± 0.2
Total N	g kg^{-1} DWE	1.65 ± 0.01	1.40 ± 0.03	0.76 ± 0.01	1.18 ± 0.01
NH_4^+-N (KCl soluble)	mg kg^{-1} DWE	5.61 ± 0.05	12.04 ± 0.19	1.34 ± 0.14	1.29 ± 0.02
TON (KCl soluble)	mg kg^{-1} DWE	19.2 ± 0.5	12.8 ± 0.3	13.7 ± 0.03	21.1 ± 0.5
Organic N (K_2SO_4 soluble)	mg kg^{-1} DWE	4.07 ± 0.21	12.10 ± 4.49	0.42 ± 0.34	BLD
Total P	mg kg^{-1} DWE	1536 ± 40	460 ± 17	487 ± 5	620 ± 35
Olsen P	mg L^{-1}	22.4 ± 0.2	5.2 ± 0.1	7.07 ± 0.1	10.3 ± 0.6
K (NH_4NO_3 soluble)	mg L^{-1}	644 ± 13	40 ± 2	53 ± 2	393 ± 9
Mg (NH_4NO_3 soluble)	mg L^{-1}	672 ± 11	144 ± 2	67 ± 0.3	548 ± 6
Cation exchange capacity (effective)	cmolc kg^{-1} DWE	25.8 ± 0.2	7.8 ± 0.04	3.2 ± 0.2	25.4 ± 0.6

2.2. *Experimental design*

Soil columns were made of PVC pipe (12.8 × 22 cm; internal diameter × depth) with the bottom covered with permeable nylon mesh (pore size = 1.5 mm x 1.5 mm) to prevent soil loss. The columns were packed with 2.86 kg of air-dry soil to a depth of 20 cm to achieve a bulk density of 1.1 g cm^{-3}. The soil columns were brought to water holding capacity through capillary action by standing them in 1 mM NaCl solution for seven days until the soil surface was visibly moist. This weak NaCl solution was used for all watering and leaching operations due to having a similar ionic strength to rainwater and causing less damage to roots and dispersion of colloids than pure water (Koopmans et al., 2005; Stutter, 2015). To avoid any water limitation, the columns were maintained at between 60 and 90% of water holding capacity throughout the experiment by daily weighing and addition of 1 mM NaCl solution. Two spring wheat (Triticum aestivum L.) plants of the cultivar 'Sokoll-N' were grown in each column (equivalent to ~ 100 kg seed ha^{-1}) to allow a sufficient soil volume for each plant and thereby avoid limitation due to low soil volume. As this is relatively low in the range of seeding rates used in Morocco, yields and NUE may differ from when higher rates are used (Karrou, 1998). The columns and plants were kept in a controlled environment room at Rothamsted Research, North Wyke, UK, at optimum temperature (24 °C day and 16 °C night time temperature) and lighting (16 h of artificial daylight with minimum light intensity of ~ 200 μmole quanta m^{-2} s^{-1}).

Fertilisers were applied to the columns at recommended (AHDB, 2024), relatively high rates (Barraclough et al., 2010) rather than at current use rates since there is scope in Morocco and Nigeria for increasing N fertiliser applications (Cassman & Dobermann, 2022). Nitrogen was applied at a total rate of 180 kg N ha^{-1} (equivalent to 18 g N m^2), with an initial application of 40 kg N ha^{-1} from each urea-based N fertiliser incorporated into the packed soil, together with phosphorus (P), potassium (K) and magnesium (Mg). The remaining 140 kg N ha^{-1} was surface applied at the tillering stage of plant growth. The N treatments were as follows: no N application (control; C), N as urea (U), N as urea with urease inhibitor (UUI), N as urea with urease inhibitor and nitrification inhibitor (UDI), and N as urea and NH_4^+ in a slow-release format (SRN). The control treatment provided information on background levels of N leaching across the soils without any fertiliser applied. For the other treatments, the fertilisers all contained 46% urea N except SRN which had 14% urea N and 10% NH_4^+-N. For the U treatment, straight urea fertiliser was sourced from Diamond Fertilisers, UK. The UUI treatment (sourced from Origin Fertilisers, UK) had the addition of N-(n-butyl) thiophosphoric triamide (NBPT) at a rate of 660 ppm. The UDI treatment contained NBPT at 600 ppm NBPT and DCD at 8500 ppm (obtained from Koch Fertilisers, USA). The SRN fertiliser was a sulphur (S) coated urea fertiliser, which also contained the urease inhibitor monocarbamida dihidrogenosulfate (Duramon®26; acquired from colleagues at Al Moutmir, Morocco). It contained S, Mg and Zinc (Zn) at rates of 26%, 2.2% and 0.1% respectively. Each fertiliser treatment was applied to four replicate cores giving a total of 20 experimental units per soil, arranged in a complete randomised block design.

2.3. *Soil column leaching and sampling*

Assessment of the fertilisers was focussed on the period after the second, larger application at the soil surface as this is where NH_3 volatilisation will be highest and inhibitors will have most affect (Macdonald et al., 2020; Rathbone & Ullah, 2023). The columns were leached with 1 mM NaCL four times at fortnightly intervals following N fertilisation, with the first event taking place 5 days after the second N application. The leachate was applied drip-wise with a multichannel peristaltic pump to give 25 mm of rainfall to each column over a 2-hour period. The columns sat on funnels to guide leachate into 500 ml conical flasks below, which were then weighed to calculate leachate volume. The samples were refrigerated immediately and analysed within 24 h of collection.

At the end of the experiment, grain and above-ground plant material were harvested at maturity, oven dried at 60 °C for 5 days or until constant weight was achieved, weighed for yield calculaion and then milled for total N analysis. After harvest, soil was removed the columns, mixed and a fresh sub-sample taken for KCl extraction (1:2 soil to 2 *M* KCl). Another soil sub-sample was taken, air dried for 7 days or until constant weight was achieved and extracted for Olsen P analysis (Olsen, 1954).

2.4. *Laboratory analysis*

Leachate pH was determined in the collection flasks using a benchtop pH meter and combination electrode (Hanna Instruments). Samples of leachate were then analysed for molybdate reactive P (a proxy for inorganic P), TON (NO_3^--N + nitrite N (NO_2^--N)), and NH_4^+-N, and following an automated digestion procedure, total P (TP) by colorimetric analysis. These were all carried out according to the instrument manufacturer's instructions (Thermo Aquachem ®). Total N (TN) and total organic carbon (TOC) were determined by Shimadzu ® TOC-L analyser according to manufacturer's instructions. Organic N (ON) and organic P (OP) were determined by difference as ON = TN − (TON + NH_4^+-N) and OP = TP – Inorganic P, respectively. Urea was measured by a modified version of the colorimetric microplate method of Greenan et al. (1995).

Total N (%) of grain and plant material was measured using a Carlo Erba NA 2000 elemental analyser (CE Instruments Ltd., Wigan, UK). Total oxidisable N and NH_4^+-N concentrations in the soil KCl extracts were analysed as above, as were inorganic P concentrations in the Olsen P extracts. Concentrations of all parameters were converted to soil surface density units of mg m^2, g m^2 or kg m^2, using data on leachate volumes, yields, soil mass and column surface area.

2.5. *Nitrogen use efficiency and N balance*

Nitrogen use efficiency was calculated as:

$$NUE = \frac{N_F - N_C}{N_R} \tag{1}$$

where, N_F and N_C are the above-ground N uptake (grain and plant material) by the plant from fertilised and control plots (g m^2), respectively, and N_R is the rate of N applied (g m^2) (Quan et al., 2021).

An N balance for each treatment in each soil was calculated by subtracting outputs from the system (N uptake into grain and plant material, and total N leaching) from inputs to the system (soil mineral N, fertiliser N and organic N mineralisation) following the approach of Louro et al. (2013). Organic N mineralisation was estimated and assumed to be equivalent to N outputs from control plots receiving no fertiliser minus initial soil mineral N.

2.6. *Statistics*

Prior to statistical analysis, all water, plant and soil response variables were log transformed to ensure normal distribution. The effects of fertiliser treatments on response variables were analysed by one-way ANOVA (Genstat Edition 22). When fertiliser had a significant effect, Tukey HSD tests were used to further identify which fertiliser treatments had a significant effect on the variables. The fits of all models were investigated in plots of residuals versus fitted values to ensure model assumptions were met. Correlations between variables were investigated using Pearson's correlations. For all analyses, results were considered significant when probability values were below 0.05.

3. Results and discussion

3.1. Nutrient leaching

Application of SRN, U and UDI fertilisers to the Beni Mellal clayey alkaline soil and application of UDI to the Ibadan sandy acidic soil significantly increased urea N leaching compared to the unfertilised soil (Table 2). However, in the Ikenne sandy acidic and Meknes clayey alkaline soils urea N leaching was not significantly increased under the N fertiliser treatments. Smaller effect sizes in these soils indicate that mineralisation of urea N may have already been complete or close to completion by the first leaching event (Table 2; Fig. 1), which highlights differences in the rate of N cycling between the soils. Previous studies have also found different rates of urea hydrolysis in different soils depending on a range of biogeochemical factors and their effects on urea N leaching (Carswell et al., 2016; Cordero et al., 2019; Singh & Bajwa, 1986). Overall, these findings align with a growing body of evidence suggesting that leaching of urea N can contribute to TN loads to surface waters (Davis et al., 2016).

The hydrolysis of urea N and the subsequent build-up of NH_4^+ in the soil is indicated by increased NH_4^+ leaching with urea-based fertilisers compared to with the unfertilised soils, except in the Beni Mellal clayey alkaline soil (Table 2; Fig. 1). This ammoniacal N is susceptible to nitrification to NO_3^- and NO_2^-. Although there was a general increase in TON leaching when urea-based fertilisers were applied, increases were not always significant for all fertilisers in all soils (Table 2; Fig. 1).

When changes in these different N forms are combined and considered as TN, the overall effect of the different urea-based fertilisers on N leaching can be more readily assessed. The application of UUI significantly increased TN leaching from all soils compared to when no fertiliser was applied (Table 2; Fig. 1). Urea alone increased TN leaching from the Ibadan and Ikenne sandy acidic soils, and SRN and UDI increased TN leaching relative to the control from the Ibadan sandy acidic soil only (Fig. 1). This suggested that application of UUI with the aim of reducing gaseous NH_3 emissions would likely increase N leaching losses. However, the addition of a nitrification inhibitor to that combination would help keep N leaching at background levels by slowing nitrification and the formation and release of highly mobile NO_3^-. Applying N in a slow-release form could have a similar effect of keeping N leaching at background levels. This could be because, with these two

Table 2

Mean and standard error ($n = 4$) of pH, carbon and nutrient loads leached from the soil columns over the course of the four leaching events grouped by soil and fertiliser type. The Beni Mellal and Meknes soils from Morocco are clayey and alkaline, whereas the Ibadan and Ikenne soils from Nigeria are sandy and acidic. Different letters between fertiliser types indicate that means are significantly ($p < 0.05$) different according to Tukey HSD post-hoc testing. Abbreviations: TOC, total organic carbon; TON, total oxidisable nitrogen; C, control; SRN, slow-release nitrogen; U, urea; UDI urea with dual inhibitor; UUI, urea with urease inhibitor.

	pH	TOC	Total N	TON	NH_4^+-N	Organic N	Urea N	Total P	Inorganic P	Organic P
	pH units	g m^2	g m^2	g m^2	mg m^2	mg m^2	mg m^2	mg m^2	mg m^2	mg m^2
Beni Mellal										
C	8.12 ± 0.05a	1.90 ± 0.04a	0.15 ± 0.01a	0.00 ± 0.00a	0.78 ± 0.30a	152 ± 13a	5.6 ± 1.8a	4.36 ± 0.74a	2.47 ± 0.29a	2.06 ± 0.32a
SRN	8.22 ± 0.02ab	2.03 ± 0.16a	0.57 ± 0.14ab	0.32 ± 0.13a	5.28 ± 2.92a	195 ± 58a	69.8 ± 21.0b	5.82 ± 0.78ab	2.81 ± 0.38a	3.01 ± 0.43ab
U	8.25 ± 0.01b	2.78 ± 0.24a	0.64 ± 0.12ab	0.30 ± 0.12a	4.84 ± 3.11a	337 ± 83a	83.4 ± 30.0b	9.32 ± 1.88b	4.49 ± 1.12a	4.83 ± 0.79b
UDI	8.29 ± 0.01b	2.18 ± 0.26a	0.58 ± 0.13ab	0.30 ± 0.06a	3.88 ± 2.63a	228 ± 72a	97.3 ± 42.9b	6.01 ± 0.78ab	2.62 ± 0.75a	3.41 ± 0.60ab
UUI	8.28 ± 0.03b	2.21 ± 0.19a	1.19 ± 0.27b	0.97 ± 0.24b	1.50 ± 0.61a	247 ± 60a	52.9 ± 24.2ab	5.53 ± 0.50ab	2.30 ± 0.21a	3.22 ± 0.40ab
Ibadan										
C	6.27 ± 0.07a	0.95 ± 0.10a	0.53 ± 0.15a	0.35 ± 0.12a	3.22 ± 1.54a	179 ± 43a	4.9 ± 1.5a	4.44 ± 0.91a	0.36 ± 0.10a	4.18 ± 0.94a
SRN	6.56 ± 0.01b	0.88 ± 0.09a	2.30 ± 0.56b	2.22 ± 0.59b	3.51 ± 0.46ab	109 ± 23a	24.0 ± 10.2ab	3.42 ± 0.62a	0.45 ± 0.14a	3.10 ± 0.73a
U	6.33 ± 0.05ab	0.72 ± 0.03a	3.82 ± 0.91b	3.61 ± 0.78b	13.94 ± 2.88b	151 ± 45a	41.1 ± 19.4ab	3.60 ± 0.85a	0.31 ± 0.08a	3.40 ± 0.84a
UDI	6.39 ± 0.06ab	0.84 ± 0.24a	3.68 ± 0.58b	3.40 ± 0.44b	17.56 ± 5.58b	279 ± 160a	143.4 ± 85.5b	2.79 ± 0.50a	0.48 ± 0.12a	2.42 ± 0.45a
UUI	6.43 ± 0.08ab	0.81 ± 0.08a	3.18 ± 0.54b	2.87 ± 0.53b	11.56 ± 2.60b	290 ± 32a	58.8 ± 23.1ab	3.94 ± 0.50a	0.58 ± 0.23a	3.47 ± 0.57a
Ikenne										
C	6.43 ± 0.03b	0.88 ± 0.14a	0.09 ± 0.02a	0.01 ± 0.01a	0.95 ± 0.47a	83 ± 22a	5.6 ± 1.0a	8.46 ± 1.71a	4.70 ± 1.73a	3.88 ± 0.57a
SRN	6.00 ± 0.05a	0.86 ± 0.09a	0.12 ± 0.01ab	0.04 ± 0.01a	6.32 ± 2.42ab	69 ± 10a	2.9 ± 0.6a	3.35 ± 0.47b	0.38 ± 0.11b	3.04 ± 0.47a
U	6.28 ± 0.02b	0.89 ± 0.13a	0.49 ± 0.16bc	0.43 ± 0.15b	14.70 ± 5.62b	54 ± 8a	7.8 ± 2.8a	3.14 ± 0.22b	0.73 ± 0.09b	2.47 ± 0.30a
UDI	6.25 ± 0.09b	0.73 ± 0.07a	0.10 ± 0.02ab	0.02 ± 0.01a	7.92 ± 0.71b	73 ± 12a	5.4 ± 0.7a	5.40 ± 0.93ab	1.36 ± 0.35ab	4.10 ± 0.72a
UUI	6.37 ± 0.03b	0.98 ± 0.03a	0.61 ± 0.11c	0.53 ± 0.12b	12.50 ± 4.09b	68 ± 7a	6.2 ± 1.8a	5.31 ± 0.34ab	1.10 ± 0.47b	4.29 ± 0.36a
Meknes										
C	7.98 ± 0.05a	1.49 ± 0.16a	0.15 ± 0.03a	0.01 ± 0.01a	4.21 ± 2.32a	79 ± 14a	9.6 ± 3.0a	3.40 ± 1.04a	2.00 ± 1.00a	1.41 ± 0.59a
SRN	8.14 ± 0.03ab	1.88 ± 0.20a	0.29 ± 0.08ab	0.12 ± 0.06a	31.10 ± 8.30b	155 ± 20ab	13.8 ± 3.9a	5.51 ± 1.85a	2.37 ± 1.05a	3.15 ± 0.97a
U	8.26 ± 0.03b	1.43 ± 0.14a	0.32 ± 0.08ab	0.20 ± 0.07a	9.04 ± 2.90ab	113 ± 23ab	10.3 ± 1.2a	3.95 ± 1.04a	1.95 ± 0.84a	2.00 ± 0.24a
UDI	8.24 ± 0.05b	1.60 ± 0.14a	0.24 ± 0.03ab	0.18 ± 0.12a	17.97 ± 1.60b	163 ± 9b	17.2 ± 1.5a	3.98 ± 0.91a	2.04 ± 0.45a	1.94 ± 0.47a
UUI	8.26 ± 0.03b	1.75 ± 0.10a	0.48 ± 0.14b	0.27 ± 0.11a	25.15 ± 4.76b	183 ± 21b	22.8 ± 4.6a	4.39 ± 0.79a	3.03 ± 0.79a	1.38 ± 0.23a

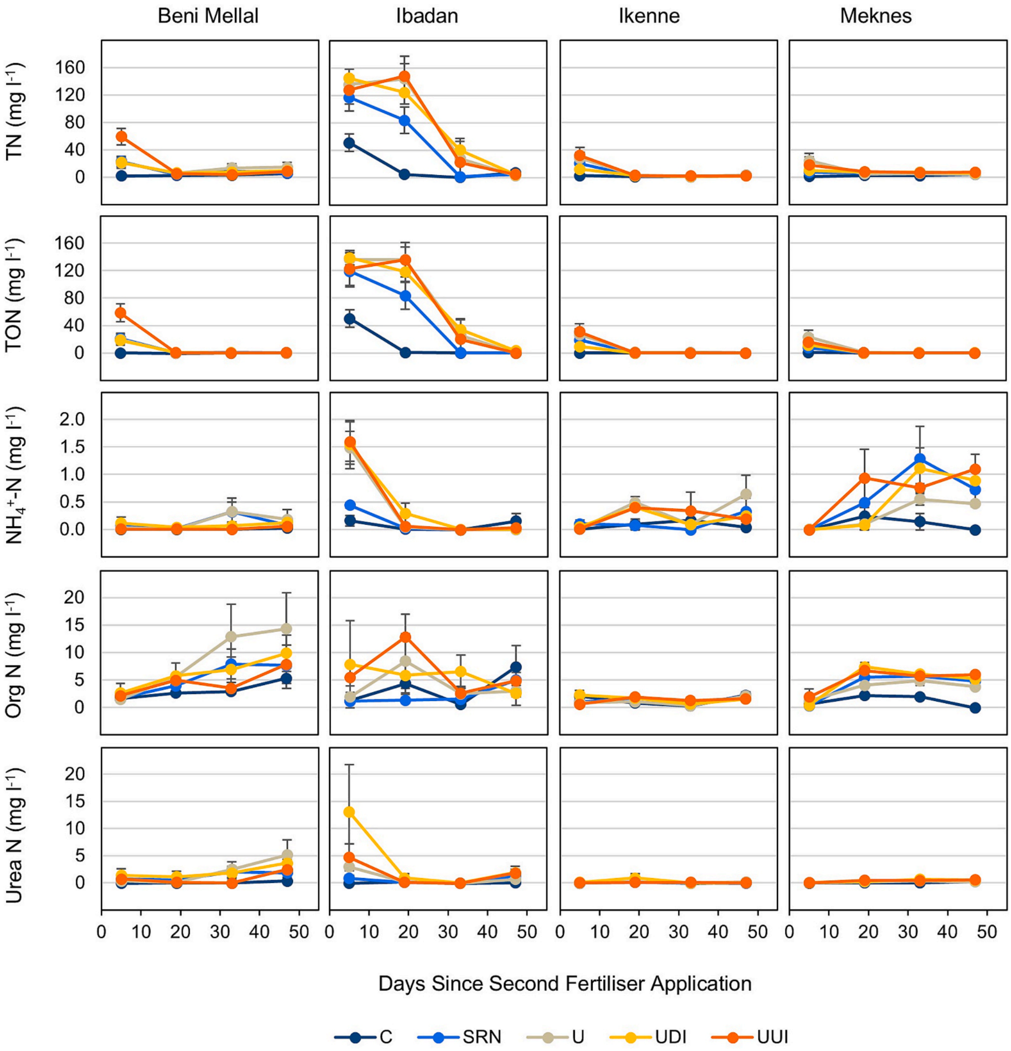

Fig. 1. Temporal trends in concentrations of N forms measured in leachate during the four leaching events according to the number of days since the second fertiliser application. The Beni Mellal and Meknes soils from Morocco are clayey and alkaline, whereas the Ibadan and Ikennes soils from Nigeria are sandy and acidic. Abbreviations: Org N, organic N; NH_4^+-N, ammonium N; TON, total oxidisable nitrogen; TN, total nitrogen; C, control; SRN, slow-release nitrogen; U, urea; UDI urea with dual inhibitor; UUI, urea with urease inhibitor. Data points are mean values and error bars show standard error (*n* = 4).

fertilisers, the urea penetrated deeper into the soil before being hydrolysed, decreasing ammonia (NH_3) volatilisation losses from the soil surface and increasing the concentration of mobile N below the root zone available for leaching. This does concur with the results of the *meta*-analysis by Wang et al. (2025) who found a far greater reduction in N leaching by urea with dual inhibitors than with urea with urease or nitrification inhibitors alone. However, in this study, these benefits were not observed in the Ibadan sandy acidic soil where soil N supply (Table 1) and N leaching (Table 2) were highest, and fertiliser N likely exceeded plant requirements. This shows the key importance of matching fertiliser rates to the soil N supply before inhibitors can have a positive effect on leaching. To investigate this further, the initial soil N supply should be considered as a factor in future *meta*-analyses like the one carried out by Wang et al. (2025). However, the positive effects of UDI and SRN were small under our experimental conditions but may differ under different conditions. For example, rainfall sooner after fertiliser application can lead to greater urea N leaching (Singh & Bajwa, 1986). There will also be differences with seeding rates, fertiliser rates, method of application and experimental set-up.

The efficiency of urea-based N fertilisers did not appear to vary with soil pH for N leaching but did for soil TON concentrations at the end of the experiment (approximately 42 days after the last leaching event and after harvesting the wheat crop). For instance, where differences between the control treatment and the fertiliser treatments were found, the effect of inhibitors was to reduce soil NO_3^- in the clayey alkaline soils from Morocco and increase soil NO_3^- in the sandy acid soils from Nigeria (Fig. 2). This could have implications for leaching losses after harvest and is likely to be a reflection of the effect of inhibitors on further N cycling after harvest, which was not measured in the present study.

Application of the fertilisers caused a general increase in pH in leachate from the Beni Mellal clayey alkaline, Ibadan sandy acidic and Meknes clayey alkaline soils compared to when no fertiliser was applied, although this was not always significant for all fertiliser types (Table 2). Increases in pH were likely due to the release of bicarbonate ions formed in urea hydrolysis ($CO(NH_2)_2 + CO_2 + 3H_2O = 2NH_4^+ + 2HCO_3^-$; Drame et al., 2023). However, the pH increase is short-lived because protons (H+ ions) are formed (a) during NH_3 volatilization ($NH_4^+ = NH_3 + H+$) and (b) during nitrification of the NH_4^+ ($NH_4^+ + 2O_2 = NO_3^- + 2H^+ + H_2O$). As a result, the soil pH gradually decreases to the original value or below it. The extent of pH changes in these acid-base reactions will depend on pH buffering by the soil which is likely to be less in the sandy Ibadan and Ikenne soils that have lower cation exchange capacity (Table 2). This may explain why, in the Ikenne sandy acidic soil, the pH was lower in leachate from SRN fertilised treatment than in the control i.

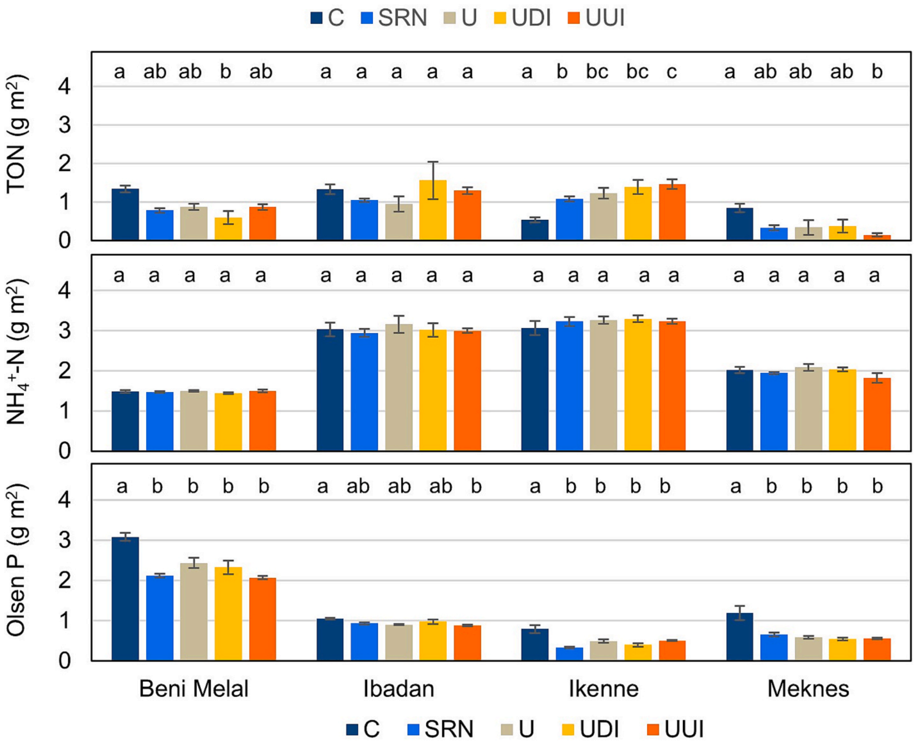

Fig. 2. Mean and standard error ($n = 4$) of soil N and P measured at the end of the experiment grouped by soil and fertiliser type. The Beni Mellal and Meknes soils from Morocco are clayey and alkaline, whereas the Ibadan and Ikennes soils from Nigeria are sandy and acidic. Different letters between fertiliser types indicate that means are significantly ($p < 0.05$) different according to Tukey HSD post-hoc testing. Abbreviations: TN, total nitrogen; TON, total oxidisable nitrogen; NH_4^+-N, ammonium N; C, control; SRN, slow-release nitrogen; U, urea; UDI urea with dual inhibitor; UUI, urea with urease inhibitor.

e. the Ikenne soil had less pH buffering against H + release from NH_3 volatilisation and nitrification of NH_4^+.

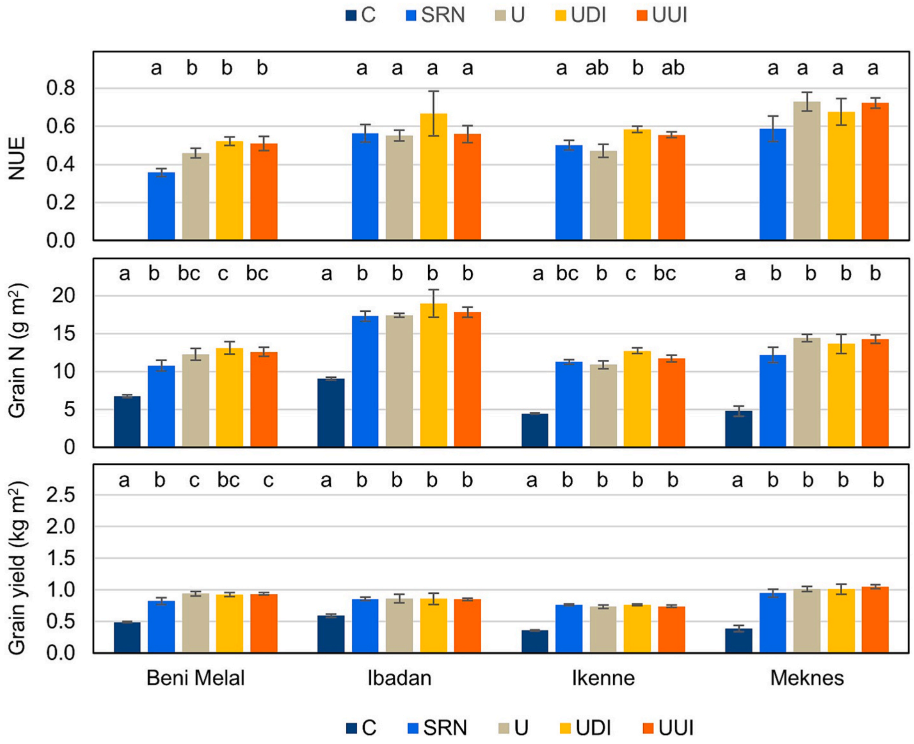

Fig. 3. Mean and standard error ($n = 4$) of grain yield, grain N and nitrogen use-efficiency (NUE) grouped by soil and fertiliser type. The Beni Mellal and Meknes soils from Morocco are clayey and alkaline, whereas the Ibadan and Ikennes soils from Nigeria are sandy and acidic. Different letters between fertiliser types indicate that means are significantly ($p < 0.05$) different according to Tukey HSD post-hoc testing. Abbreviations: NUE, nitrogen use efficiency; C, control; SRN, slow-release nitrogen; U, urea; UDI urea with dual inhibitor; UUI, urea with urease inhibitor.

Changes in soil pH may also influence P cycling. Depending on the soil type and its initial pH, an increase in pH may either increase or decrease the solubility and hence plant availability of soil P (Barrow, 2017; Hartikainen & Yli-Halla, 1996). However, in the three soils where pH increased with N fertiliser addition, there were no differences in P leaching between the N fertiliser treatments, except in the Beni Mellal clayey alkaline soil fertilised with straight urea where the leachate organic P increased (Table 2). In the Ikenne sandy acidic soil, where the pH decreased following SRN fertiliser application, leachate inorganic P decreased in the SRN and U treatments compared to the unfertilised soil. In an acid soil with pH-dependent surface charge, such as the Ikenne sandy acidic soil, a fall in pH will decrease P solubility (Barrow, 2017) and hence potential leaching. Other studies have found P solubility to remain elevated for some time after pH changes following urea hydrolysis (Hartikainen & Yli-Halla, 1996). However, these studies did not include plants withdrawing P from the soil solution. Analysis of the soils at the end of the experiment (approximately 42 days after the last leaching event) showed significant reductions in Olsen P where urea-based fertilisers were applied compared to unfertilised soil (Fig. 2). This was presumably related to the better growth and yield and hence P uptake in the fertilised treatments (Fig. 3), rather than any small transient changes in P solubility.

3.2. *Yield, N uptake, NUE and N balance*

The application of urea-based fertiliser significantly increased grain yields in all cases (Fig. 3). The inclusion of inhibitors with urea did not result in a further improvement in grain yield, unlike in many previous studies (Folina et al., 2021; Sha et al., 2020). However, these findings do agree with other studies, which also found no yield benefit of including urease inhibitors with urea fertiliser under both field and greenhouse settings (Grant, 2014; Lasisi et al., 2022). Those studies suggested that inhibitors make less of a difference when N is applied at high rates, as in this study. Indeed, across a range of studies, Wang et al. (2024) found the best improvements in crop yields by similar UUI and UDI treatments were observed at N application rates below 150 kg ha^{-1}. A similar *meta*-analysis by Rose et al. (2018) also showed that fertilisers with urease inhibitors have limited potential to enhance yield at the high N rates recommended in current guidelines. Comparing with the SRN fertiliser, there were indications in the Beni Mellal clayey alkaline soil that N applied as straight urea and with urease inhibitors increased yields compared to N in slow-release format (Fig. 3).

Results for grain N and NUE show similar patterns to yield, with significant increases in grain and stem N when urea-based fertilisers are used compared to unfertilised soil. Comparing fertiliser with biochemical inhibitors, there was no effect of including urease inhibitors on grain N or NUE, except in the Ikenne sandy acidic soil where UDI increased grain N compared to U (Fig. 3). There was no such difference for stem N. This contrasts with Wallace et al. (2020) who found improvements in N uptake and NUE when urease inhibitors were included with urea fertiliser applied at a low N rate of 50 kg ha^{-1}. It is possible that the guidance rate of 180 kg ha^{-1} used here for all fertilisers provided sufficient N for uptake and grain filling regardless of the action of the inhibitors. Lasisi et al. (2022) also reported statistically similar N uptake and NUE for canola and wheat fertilised with urea with and without a urease inhibitor, which they attributed to an N surplus coming from soil residual and mineralised N. Likewise, in the Ibadan soil where soil N supply and background N leaching were highest, the results of this study also showed no effect of different fertiliser types on any of the nutrient parameters measured.

Comparing with the SRN fertiliser, grain N was greater with the UDI treatment than the SRN treatment in the Beni Mellal clayey alkaline soil, and NUE was greater with the UDI treatment than the SRN in the Ikenne sandy acidic soil. These results, and those discussed above, suggest that N release from the dual inhibitor fertiliser could be better aligned with the timing of plant uptake, allowing for more N uptake during growth and more N available for grain filling. Indeed, N uptake can be enhanced when nutrients are released to suit plant-specific growth nutrient requirements over time (Liu et al., 2023). Guardia et al. (2021) also found this to be the case when dual inhibitors were used i.e. the double inhibitor used significantly improved N use efficiency.

An overall N balance gave additional insight into N cycling across the soils and treatments (Table 3). The N balance for the control treatments was always zero, since no fertiliser was applied and supply of N for plant uptake and N leaching was assumed to be from the soil mineral and organic N pool. However, the N balance was positive for all fertiliser treatments across all soils. Nitrogen balance values were lowest in the Ibadan sandy acidic soil, despite having the highest values of apparent organic N mineralisation. In three of the four soils, the SRN fertiliser had the highest balance value, which may be due to the generally lower N leaching and lower plant N uptake from this treatment. These findings also suggest that fertiliser N may have been applied in excess, with the surplus N being available for losses to the atmosphere or transformation back into the organic N pool.

4. Conclusions

The aim of this study was to assess the efficiency of a range of different urea-based fertilisers for reducing nutrient leaching from contrasting soils from Mediterranean and sub-Saharan Africa. The highest N leaching loads when fertilisers were applied were observed for the Ibadan sandy acidic soil where soil N supply was highest and fertiliser was likely to have been applied in greatest excess. This shows the importance of first matching fertiliser rates to N supply from the soil, and this would make the biggest difference for reducing N leaching. Once this is achieved then fertiliser types can be adjusted to further reduce N leaching. Our results suggest urea with both a urease and nitrification inhibitor or slow-release urea N would be most effective for this purpose. Although yields were similar between these two fertilisers, the dual inhibitor proved better for maintaining NUE than the slow-release fertiliser in two of the four soils. The urea with a urease and nitrification inhibitor is therefore the recommended fertiliser for reducing N losses via leaching while simultaneously maintaining yield and NUE. There was little evidence to suggest that soil pH affected the efficiency of this fertiliser for reducing N leaching. However, these findings are highly dependent on experimental conditions such as seeding rates, fertiliser rates, method of application and experimental set-up. To achieve the greatest effect, fertilisers should be assessed at the local level in field trials and be adapted to match local conditions. Where this cannot be achieved, this study, which covers a range of fertilisers and soil conditions, provides initial guidance to agronomists and catchment managers about which fertilisers to use/recommend where and under what conditions to reduce leaching losses and protect water quality.

CRediT authorship contribution statement

W.M. Roberts: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Raklami:** Writing – review & editing, Methodology, Investigation. **M. Drame:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **G.J.D. Kirk:** Writing – review & editing, Funding acquisition, Project administration. **M. Jemo:** Writing – review & editing, Resources, Project administration, Funding acquisition. **T.H. Misselbrook:** Resources, Project administration, Funding acquisition. **A.M. Carswell:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial

Table 3
Nitrogen balance for each treatment in each soil showing inputs to the system (soil mineral N, fertiliser N and organic N mineralisation), outputs from the system (N uptake into grain and plant material, and total N leaching) and N balance in g m^2. Abbreviations: C, control; SRN, slow-release nitrogen; U, urea; UDI urea with dual inhibitor; UUI, urea with urease inhibitor.

	Initial mineral N	Fertiliser N	Organic N mineralisation	N inputs	N leaching	Plant N uptake	N outputs	N Balance
Beni Mellal								
C	5.5	0	3.3	8.8	0.2	8.6	8.8	0.0
SRN	5.5	18	3.3	26.8	0.6	15.1	15.6	11.1
U	5.5	18	3.3	26.8	0.6	16.9	17.5	9.2
UDI	5.5	18	3.3	26.8	0.6	18.0	18.6	8.2
UUI	5.5	18	3.3	26.8	1.2	17.8	19.0	7.8
Ibadan								
C	5.5	0	6.5	11.9	0.5	11.4	11.9	0.0
SRN	5.5	18	6.5	29.9	2.3	21.5	23.8	6.1
U	5.5	18	6.5	29.9	3.8	21.3	25.1	4.8
UDI	5.5	18	6.5	29.9	3.7	23.4	27.1	2.8
UUI	5.5	18	6.5	29.9	3.2	21.5	24.7	5.3
Ikenne								
C	3.3	0	2.8	6.1	0.1	6.0	6.1	0.0
SRN	3.3	18	2.8	24.1	0.1	15.1	15.2	8.9
U	3.3	18	2.8	24.1	0.5	14.5	15.0	9.1
UDI	3.3	18	2.8	24.1	0.1	16.6	16.7	7.5
UUI	3.3	18	2.8	24.1	0.6	16.0	16.6	7.5
Meknes								
C	4.9	0	2.5	7.4	0.1	7.2	7.4	0.0
SRN	4.9	18	2.5	25.4	0.3	17.8	18.1	7.3
U	4.9	18	2.5	25.4	0.3	20.4	20.7	4.7
UDI	4.9	18	2.5	25.4	0.2	19.4	19.6	5.7
UUI	4.9	18	2.5	25.4	0.5	20.2	20.7	4.7

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data used in this study are available on the Rothamsted Data Repository at https://data.rothamsted.ac.uk

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