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Maize yield response to nitrate leaching at early growth stage under crop and site-specific biosolid application

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ABSTRACT

Biosolid applications based on crop nitrogen (N) demand have been widely adopted to attenuate nitrate leaching. However, due to the dependence of N supply on the mineralization rate and the early release of the majority of the mineralizable N, there are concerns about a compromise in crop yield and groundwater. A two-year field lysimeter study was conducted to verify whether higher nitrate leaching from biosolid at the early growth stage would compromise maize yield compared to a two-split inorganic N fertilizer application. Four treatments (biosolid + humid rainfall, inorganic fertilizer + humid rainfall, biosolid + subhumid rainfall, inorganic fertilizer + subhumid rainfall) replicated three times were randomly allocated to 12 lysimeters. Overall, the cumulative nitrate leaching from biosolid application was comparable to inorganic fertilization. Nitrate leaching at the early (V0–V14) growth stage of maize from biosolid was lower than inorganic fertilizer, except in the second year under humid rainfall. However, nitrate leaching did not compromise maize yield. Thus, biosolid application based on crop and site specificity can replace inorganic fertilizer in maize cultivation. Further studies may need to ascertain the findings in the humid agro-ecological zone because of the high soil N residue observed under biosolid-humid rainfall treatment.

1. Introduction

Nitrogen (N) fertilization substantially impacts cereal output and helps ensure global food security (Liang, 2022; Tyagi et al., 2022; Ahmed et al., 2017). According to Tyagi et al. (2022), cereal cropping uses around 55% of the commercially produced N fertilizer, but its production is not sustainable (Menegat et al., 2022; Mulvaney et al., 2009). By 2050, overall carbon emissions could reach a record high due to the current trajectory in N fertilizer output (Lim et al., 2021). Excessive carbon emissions might compromise food security and the future net zero carbon emission target (Liu et al., 2022). Biosolid, a processed and stabilized sludge from wastewater treatment plants, is currently attracting much interest as a green substitute for nitrogen fertilizer (Poornima et al., 2022; Yang et al., 2018). There is a potential to lessen reliance on commercial inorganic fertilizers and ensure environmental sustainability through biosolid land application.

The use of biosolids in agricultural applications could benefit environmental sustainability. However, nitrate leaching from biosolid and inorganic fertilizer applications has been a long-standing challenge (Lu et al., 2022; Hussain et al., 2019; Mary et al., 2008). Biosolid is often applied based on crop N requirements to address this issue. In addition, the application time and method, land suitability factors, temperature and rainfall are considered (Rigby et al., 2016). This N management strategy focuses on crop and site-specificity, with examples such as the Sludge Application Rate Advisory (SARA) model by Tesfamariam et al. (2015b) and the biosolid agronomic rate worksheet by Sullivan et al. (2021).

About 70% of the biosolid N is in organic form and is subject to mineralization, in contrast to the readily available N in inorganic fertilizers. Under certain momentary environmental conditions (such as heavy rainfall events), mineralized N in nitrate form may leach out of the root zone, thus reducing its availability for crop absorption (Tesfamariam et al., 2015a; Gabriel et al., 2012). Several studies have shown significant N mineralization during the first few days to weeks of application (Medina-Herrera et al., 2022; Badza et al., 2021; Hseu and Huang, 2005). Extrapolates from these studies suggest vulnerability to N leaching in high rainfall events during the early growth stage (Awal et al., 2021). Hence, it may compromise crop yield. Despite this, little is known about the trade-off between nitrate leaching and crop yield due to high rainfall at the early growth stage.

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In South Africa, maize is typically planted between November and February, at the peak of the summer rainy season. Maize requires high N uptake for optimum yield, especially during the vegetative and reproductive stages (Bender et al., 2013). Due to this, it is a common practice to apply commercial N fertilizer in split to improve N use efficiency and reduce N loss through leaching. According to studies (Pampana et al., 2021; Barbarick et al., 2017; Cogger et al., 2013; Koenig et al., 2011), the slow N release from biosolid matches crop N requirement. However, because biosolid N mineralization could peak before the critical growth stage of maize, it was hypothesized that higher nitrate leaching from biosolid-amended soil would compromise maize yield compared to the two-split inorganic N fertilizer application. A previously developed SARA model used to estimate crop- and site-specific biosolid application rates (Tesfamariam et al., 2015b) served as the paradigm for this study. The objectives were to (1) quantify maize yield and nitrate leaching and (2) determine the relationship between maize yield and nitrate leaching in the early (V0–V14) growth stage of maize in crop- and site-specific biosolid amended soil using commercial inorganic fertilizer as a benchmark.

2. Materials and methods

The crop and site-specific biosolid application rates were estimated using the SARA model parameterized for the study site. The parameters used for the estimation included the physicochemical properties of the biosolids and soil (Table 2). The application method was “incorporated”, the cropping system was “dryland”, and the crop type was “maize” for the humid and subhumid agro-ecological zones (Tesfamariam et al., 2015b).

2.1. Experimental site

A two-year field study was conducted at a lysimeter facility at the Hatfield Experimental Farm, University of Pretoria (latitude 25°45'S, longitude 28°16'E, and 1370 m.a.s.l). Pretoria is situated within the sub-humid agro-ecological zone of South Africa, with an average annual rainfall of 600–800 mm (Gbetibouo and Hassan, 2005).

2.2. Field set-up

Twelve lysimeters were set up in two rows, with six lysimeters on either side of the underground housing (Fig. S1). Between lysimeters on each row was a spacing of 0.8 m. Each lysimeter was a metal-built cylinder (2.4 × 1.3 m) packed with uniform soil layers. The soil monoliths were not disturbed for more than three decades; therefore, they were assumed to be in an absolute natural state. The lysimeter’s rim was 12 cm above the soil surface and contained well-drained topsoil. Thus, runoff during heavy rainfall was unlikely. High-density polyethene drip irrigation pipes (2 cm in diameter) were installed on the humid rainfall treatment plots. Water meter access tubes were fixed at the centre of each lysimeter for soil water meter readings.

Large plastic drums (capacity 120 L) were placed inside the underground housing beneath each lysimeter column (Fig. S2). Each plastic drum had a valve at the base for leachate collection and a lid to avert external contaminants.

2.3. Soil and weather data

Soil water content was measured using a site-calibrated neutron meter (Model 503 DR CPN Hydroprobe; Campbell Pacific Nuclear, CA, USA). The neutron water meter was calibrated using a vacant lysimeter devoid of plants. Weekly or bi-weekly readings, depending on the rainfall, were recorded throughout the maize-growing period.

Weather data for the sub-humid zone were collected from an automated weather station less than 500 m from the experimental site. Weather data from the SASRI weather station (https://sasri.sasa.org.za/pls/sasri/weatherweb/r/home/login_desktop?session=2243946111716) in Durban represented a humid zone. Table S1 shows the mean maximum, minimum, and average temperatures and the total rainfall for both regions during the study period.

2.4. Treatments and experimental design

Four treatments (biosolid + humid rainfall, biosolid + sub-humid rainfall, inorganic fertilizer + humid rainfall, and inorganic fertilizer + sub-humid rainfall) were randomly allocated to the lysimeters and replicated three times. The concrete bed-dried anaerobically digested biosolids (Table S2) used for the trials were collected from East Rand Waterworks, Johannesburg, South Africa. Biosolid and commercial inorganic fertilizers were applied based on recommendations from the SARA model and the Fertiliser Society of South Africa Handbook (FSSA, 2007), respectively. In the first year, biosolid was applied at 16.5 Mg ha^{-1} + 104 kg KCl ha^{-1} and 31.7 Mg ha^{-1} + 160 kg KCl ha^{-1}, while the inorganic fertilizer application rate was 155:63:104 kg NPK ha^{-1} and 258:69:160 kg NPK ha^{-1} for the sub-humid and humid rainfall treatments, respectively. In the second year, biosolid was applied at 1.6 Mg ha^{-1} + 33.4 kg KCl ha^{-1} and 12.7 Mg ha^{-1} + 40.7 kg KCl ha^{-1}, whereas inorganic fertilizer was applied at 145:22:26 kg NPK ha^{-1} and 220:30:53 kg NPK ha^{-1} for the sub-humid and humid rainfall, respectively.

2.5. Land preparation, treatment application, and planting

The land was tilled using a hoe. Biosolid and inorganic fertilizers were manually broadcasted and immediately incorporated into the top 0–10 cm of the soil. One day later, maize seeds (PAN 6439 for the first year and IMP 52-11R for the second year) were sown at a rate of 40,000 (sub-humid) and 60,000 (humid) seeds ha^{-1} at a depth of 3 cm. Maize seeds were supplied by Pannar Seed®, South Africa.

Phosphorus was applied once at planting for the inorganic fertilizer treatments. Potassium (K) and N were applied in two splits: 30% at planting and 70% at seven weeks after planting. Because of the low K content of biosolids (Tesfamariam et al., 2015a), K was added to all biosolid treatments in the form of KCl, as estimated by the SARA model.

2.6. Biosolid incubation for mineralization studies

To quantify the N mineralized from the applied biosolid, a soil-biosolid mix was incubated in a porous ceramic cup in biosolid-treated lysimeters at a depth of 10 cm (Henry et al., 2000).

Organic N (ON) mineralization was calculated as follows:

$$\text{ON mineralization} = \frac{(M_0 \times ON_0) - (M_1 \times ON_1)}{(M_0 \times ON_0)}$$

where M_0 = Initial mass of biosolid

M_1 = Final mass of the biosolid
ON_0 = Initial concentration of organic N
ON_1 = Final concentration of organic N.

2.7. Irrigation and simulation of humid rainfall

During the establishment stage, all plants received 10 mm uniform irrigation every 3–4 days without rainfall until six weeks after emergence in the 1st year and until four weeks after emergence in the 2nd year.

Because the experiment was conducted in a sub-humid region, humid treatments intermittently received supplemental rainfall through pressure-compensated drippers operating at 100 kPa. The simulation of humid rainfall was based on ten-year data from Durban, South Africa (a humid agro-ecological zone). The data showed that the humid area averaged approximately 110 mm more rainfall than the subhumid zone. Hence, 10 or 20 mm of irrigation was chosen as the top-up for the wetter months (January–March) and 5 mm for the drier months (April and May). Irrigation was spread across the growing period. Rainfall was simulated during dry periods and did not exceed the maximum monthly frequency of rainfall in the humid agro-ecological region. Rainfall simulation was terminated when the crop reached physiological maturity.

The total rainfall during the maize growing/summer season (mid-November to May) was 524.6 mm in the first year and 708.6 mm in the second year for the subhumid region (Pretoria). The humid area (Durban) had 909.5 mm and 694.5 mm of rainfall in the first and second years, respectively. During the field trial, however, the total actual rainfall amount in the humid agro-ecological region (Durban) was 689.1 mm in the first year (28th December 2018–6th June 2019) and 398 mm in the second year (6th February–31st May 2020). The total rainfall in the second year was lower than in the first year because of late planting in the second year.

However, the actual humid (Durban) rainfall during the first and second years of planting was similar to the total rainfall applied under humid rainfall treatments, as presented in Table 1.

2.8. Sampling

2.8.1. Leachate

After every percolation from rainfall events, the total volume of leachate from each drum was measured, and a 100 ml sample was analyzed immediately.

2.8.2. Soil

Soil samples for physicochemical diagnostics were collected using a 10 cm diameter cup-sized soil auger (Johnson Soil Augers, South Africa). The soil was sampled from the centre of each lysimeter at 0–30, 30–60, and 60–100 cm depth intervals before and after the trials. The samples were prepared for laboratory analysis by air-drying and passing through a 2 mm sieve (Endecotts Limited, London, England). Undisturbed core soil samples were collected from a vacant lysimeter for bulk density determination.

2.8.3. Plant

Ear leaves were sampled at the silking stage and grain at harvest for N content. Whole plant samples were collected from each lysimeter at physiological maturity to determine the above-ground biomass. The biomass was oven-dried (Forced circulation incubator FSIE 16. Labcon, Roodepoort, South Africa) at 65 °C to a constant mass and weighed. Biomass was further partitioned into leaves, stems, and grains and weighed.

2.9. Physicochemical analysis of soil, plant, biosolid and leachate

The Walkley and Black (1934) method was used to determine the organic matter content of soil and biosolid. Total P and heavy metals in biosolid were extracted by microwave-assisted nitric acid digestion, as Tam and Yao (1999) explained. pH and EC meters (Consort C830 and C861, Turnhout, Belgium) were used to measure the pH and EC in a 1:2.5 soil/biosolid: distilled water slurry. Plant available P in the soil was estimated using the Bray-1 extraction method, as Sims (2000) outlined. Soil exchangeable acidity was extracted in 1M KCl (Thomas, 1982). Exchangeable bases in the soil and biosolids were extracted in 1M NH_4OAc. The extracted total P, available P, and exchangeable bases were measured using ICP-OES (SpectroFlame Modula: Spectro, Kleve, Germany). The soil effective cation exchange capacity (ECEC) was then calculated as the sum of 1M NH_4OAc extractable bases and 1M KCl extractable acidity. Nitrate and ammonium were extracted from the soil and biosolid using 1M KCl and measured colourimetrically using a UV/visible spectrophotometer (Pharmacia LKB – Ultraspec III, Cambridge CB4 4FJ, UK). Total nitrogen in the soil, biosolids, and plant and total carbon in the plant samples were analyzed by the complete combustion method as detailed by Sollins et al. (1999) using a Carlo Erba NA 1500 C/N analyzer (Carlo Erba Strumentazione, Milan, Italy). The NO_3^--N concentration in the leachate was determined using a nitrate test kit (Merck cat. no. 1147730001) by reacting with nitrospectral in concentrated H_2SO_4. Nitrate was then analyzed using a multiparameter colourimeter (Move 100 Spectroquant®, model 173632, Merck Germany) with a 0.5–15.0 (±0.31 accuracy) mg l^{-1} NO_3^--N measurement range. The mass of leached NO_3^--N was calculated as the concentration multiplied by the leachate volume.

Soil textural class was determined using the hydrometer method. Bulk density was determined using the core sampler method, and biosolid moisture content was determined using the gravimetric method.

2.10. Statistical analysis

One-way ANOVA evaluated the combined effects of fertilization + rainfall on each year's NO_3^--N leaching and maize yield. Two-way ANOVA was employed to test the impact of the year on NO_3^--N leaching and maize yield, with fertilization + rainfall and year as factors. Nitrate leaching was regressed using linear and stepwise regression models to predict the maize grain and biomass yields. The Tukey test separated the significant means at the 5% probability level. Statistical analyses were performed using SPSS (IBM SPSS 28.0.1.0).

3. Results and discussion

3.1. Soil and biosolid properties

The physicochemical properties of the soil before the first year of the field trial are listed in Table 2A. Generally, the lysimeters contained soils of similar textural classes (only the topsoil textural class is shown) down the profile. The similarity in soil texture provided a fair comparison of nitrate (NO_3^-) leaching among treatments. The clay fractions in all strata of the soil profile were moderate to high, ranging from 30 to 41%. The topsoil (0–30 cm) was sandy clay loam, whereas the subsoils (30–60 and 60–100 cm) were either clay loam or clay. The sand: clay ratio at 0–30 cm and 30–60 cm depths was less than 0.9, indicating reasonably

Table 1
Total amount of irrigation and rainfall (natural and simulated) in mm during the trials.

		First-year (28 December 2018–6 June 2019)				Second-year (6 February–31 May 2020)			
		Natural rainfall	Uniform irrigation	Simulated rainfall	Total rainfall received	Natural rainfall	Uniform irrigation	Simulated rainfall	Total rainfall received
Humid	In–H	398.8	75	135	608.8	228.9	35	120	383.9
	Bio–H	398.8	75	135	608.8	228.9	35	120	383.9
Sub-humid	In–S	398.8	75		473.8	228.9	35		263.9
	Bio–S	398.8	75		473.8	228.9	35		263.9

In = Inorganic fertilizer, S = Sub-humid rainfall, Bio = Biosolid, H = Humid rainfall.

Table 2

Physico-chemical properties of topsoil and biosolid as used in the estimation of biosolid and inorganic fertilizer application rates (n- = 3).

	Moisture	Sand	Clay	Silt	Texture	pH (H_2O)	Bray-1 P	K	NO_3^--N	NH_4^+-N	Total N	Organic C	Total P
	%						mg kg^{-1}				%		
A: Soil properties before the first-year trial treatment application													
In–H		53 ± 0.8	30 ± 1.8	17 ± 1.3	SCL	5.2 ± 0.11	13.51 ± 2.6	30.40 ± 1.6	4.47 ± 0.5	12.35 ± 5.0	0.057 ± 0.005	0.63 ± 0.10	
Bio–H		50 ± 1.8	33 ± 2.1	17 ± 0.3	SCL	5.3 ± 0.06	7.79 ± 1.1	30.20 ± 2.3	5.44 ± 0.4	11.04 ± 1.9	0.069 ± 0.004	0.67 ± 0.06	
In–S		52 ± 1.4	32 ± 1.4	16 ± 0.3	SCL	5.2 ± 0.11	12.55 ± 2.6	32.71 ± 1.7	3.56 ± 0.8	6.73 ± 0.3	0.061 ± 0.003	0.65 ± 0.03	
Bio–S		50 ± 0.4	34 ± 1.8	16 ± 1.8	SCL	5.1 ± 0.13	11.12 ± 1.2	32.17 ± 2.7	6.48 ± 3.7	9.45 ± 2.1	0.065 ± 0.002	0.62 ± 0.04	
B: Soil properties after first year trial crop harvest and before second year trial treatment application													
In–H							27.64 ± 1.9	112.5 ± 9.0	10.49 ± 0.7	4.76 ± 0.9	0.107 ± 0.012		
Bio–H							32.49 ± 2.6	120.7 ± 16.0	19.91 ± 5.4	3.86 ± 1.2	0.133 ± 0.012		
In–S							29.04 ± 2.2	135.8 ± 6.4	12.87 ± 5.3	3.49 ± 0.6	0.097 ± 0.007		
Bio–S							22.14 ± 2.8	96.0 ± 4.2	23.52 ± 7.0	4.00 ± 1.0	0.103 ± 0.009		
C. Physicochemical properties of the biosolid used in the study													
1st year trial	25					6.5		180.86	21.98	22.08	2.71		1.5
2nd year trial	27					6.9		3145.5	24.13	26.91	3.40		3.0

In = Inorganic fertilizer, S = Sub-humid rainfall, Bio = Biosolid, H = Humid rainfall.
SCL = Sandy clay loam.
± standard error of mean.

drained soils. The topsoil was moderately acidic with a pH of 5.2 ± 0.1 but within the optimal range (5–7) for most microbial group activities (Pietri and Brookes, 2008) controlling N mineralization. The soil lacked adequate essential plant nutrients (FSSA, 2007), and ECEC ranged between 1.3 and 1.6 meq/100 g. Like most annual crops, maize requires a high N input (Nasielski et al., 2019; Dai, 1998), and uptake occurs mainly in the form of NO_3^-. Soil NO_3^--N was below the lower limit of the optimum range (20–25 mg kg^{-1}) for maize crops (Blackmer et al., 1989).

Before the second-year trial, the soil nutrient composition showed increases in total N and NO_3^--N but decreased NH_4^+-N concentrations (Table 2B) relative to the initial soil properties (Table 2A). Given that the initial pH of the topsoil (Table 2A) and biosolids (Table 2C) were relatively low and with the immediate incorporation of biosolid and inorganic fertilizer into the soil at application, it is assumed that N losses through volatilization would be insignificant (Dari et al., 2019; Henry et al., 1999). The decrease in NH_4^+ was attributed to nitrification, amplified by the increased microbial activities from biosolid application (Norton and Ouyang, 2019; Nugroho et al., 2006). This finding agrees with He et al. (2000), where NO_3^- was the consistently dominant mineral N after periodic mineralization evaluations, despite NH_4^+ being the higher N mineral before the experiment. In contrast, a previous study on biosolid N mineralization in the sub-humid and humid agro-ecological regions in South Africa showed decreases in both NO_3^- and NH_4^+ after one year of incubation using porous ceramic cups (Badza et al., 2020). This reduction may be due to the low clay fraction (10–18%) of the soils used in the soil-biosolid mix, implying that nitrification may have occurred, but NO_3^- was lost to the surrounding soil outside the porous ceramic cups.

The inorganic N concentrations of biosolids for both years were less than 1%, indicating that approximately 99% of the total N was organic. It was surprisingly higher than that reported for most biosolids. However, heat-dried anaerobically digested biosolids contain more than 90% organic N owing to NH_4^+-N volatilization during drying (Sullivan et al., 2015). Therefore, nitrate leaching from applying such biosolids is highly dependent on the rate of N mineralization. The C: N ratio of the biosolids used in this study was 6, within the range of optimum N mineralization (Brust, 2019).

3.2. Fertilization and year effects on maize yield

Biosolid application produced a similar maize yield to inorganic fertilizer. The exception was under the sub-humid rainfall in the 2nd year, where maize grain yield from the inorganic fertilizer treatment was significantly ($P < 0.01$) higher than that of the biosolid treatment (Fig. 1). This was in contrast to the previously simulated results for grain yield in the areas of focus (humid and sub-humid agro-ecological zones of South Africa), which showed significantly ($P < 0.05$) higher grain yield in biosolids than in inorganic fertilizers (Ogbazghi et al., 2019). Nonetheless, similar or higher yields from biosolid applications than inorganic fertilizers have been widely reported (Barbarick et al., 2017; Cogger et al., 2013; Koenig et al., 2011). In the current study, the maize

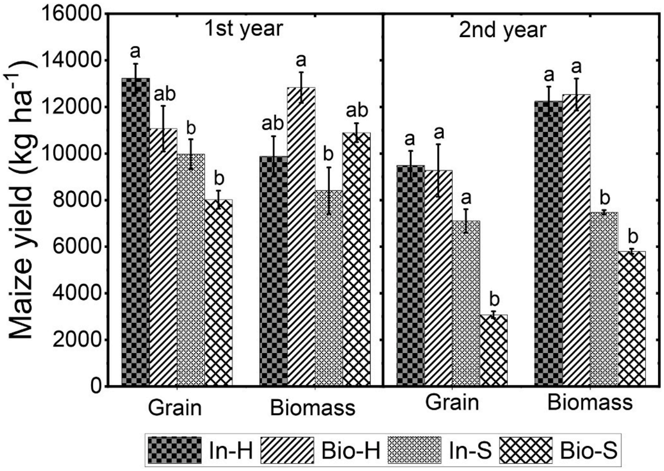

Fig. 1. Maize grain and biomass yields as affected by biosolid versus inorganic fertilizer under humid and sub-humid rainfall distribution. Significant difference was determined by Tukey test ($P < 0.05$). Alphabets indicate significance of treatment means within a particular yield type. In = Inorganic fertilizer, Bio = Biosolid, S = Subhumid rainfall, H = Humid rainfall.

grain yield was either above or within the target range of 8000 kg ha^{-1} for sub-humid rainfall and 11,000 kg ha^{-1} for humid rainfall (FSSA, 2007) in the first year but lower than the target yield in the second year. Regarding the target yields, the percentage decreases in grain yield in the second year were 14%, 16%, 11% and 62% for In–H, Bio-H, In–S, and Bio-S, respectively.

The drastic drop in maize grain yield during the second year may be attributed to the low rainfall (Table 1) experienced during the establishment and vegetative growth stages (Fig. 5b). About 300 mm of rainfall was missed before planting. The decline in yield was more severe in the Bio-S plot than in other treatments, mainly due to decreased biosolid N mineralization (Fig. S5) and uptake (Table S4). According to the field incubation study, N mineralization during the second year was approximately 8% (humid) and 10% (sub-humid) lower than that in the first year. Therefore, it was speculated that the effect of low rainfall on biosolid-treated plots was two-fold. Water deficiency directly impacts photosynthesis and dry matter production (Jain et al., 2019; Osakabe et al., 2014; Lisar et al., 2012; Shinozaki, 2003). It also indirectly decelerates organic matter decomposition, delaying nutrient release (Walter et al., 2020; Nguyen et al., 2018).

Furthermore, the combination of low average temperature and total rainfall at the onset of the reproductive stage on the 2nd and 3rd week of March 2020 (Table S1) may have contributed to the variations in treatment effects across the years (Fig. S3). Notwithstanding the insignificant effect in the year × (fertilization + rainfall) interaction on grain yield (Table S3). Previous studies have reported that other than biosolid N supply, meteorological factors also impact yearly fluctuations in N uptake (Pampana et al., 2021; Barbarick and Ippolito, 2007).

3.3. Fertilization and year effects on cumulative nitrate leaching

Cumulative nitrate leaching was not influenced by year, fertilization + rainfall, or the combination (Table S3). The cumulative nitrate leaching, as affected by the experimental treatments for each year, is shown in Fig. 2. Percent differences showed that Bio-H had higher nitrate leaching than In–H by 20% and 66%, while Bio-S had lower nitrate leaching than In–S by 23% and 54% in the 1st and 2nd year, respectively.

Of the total N applied during the 1st year, 17% (In–H), 6% (Bio–H), 22% (In–S), and 6% (Bio–S) were lost via leaching. In the 2nd year, 31%, 21%, 8%, and 9% of the applied N in In–H, Bio–H, In–S, and Bio–S were leached through the soil profile.

Low rainfall (see Tables 1 and S1), in conjunction with periodic heavy rainfall events, was suggested as a probable cause for the relatively higher nitrate leaching from the humid rainfall treatment during the 2nd year, compared with similar treatments in the 1st year (see Fig. 4). Between 23/03/ and 30/03/2020 (42nd and 49th day after germination (DAG)) in the 2nd year there was little (<5 mm) or no daily rainfall, followed by 10 mm rainfall on the 50th DAG (31/03/2020) and three consecutive days (53rd – 55th DAG or 03/04/ – 05/04/2020) of relatively heavy rain (total 77.8 mm), resulting in relatively high mean cumulative leaching (54th – 58th DAG or 04/04/ – 08/04/2020) of 15 and 23 kg NO_3^--N ha^{-1} for the biosolid and inorganic fertilizer treatments, respectively. A previous study showed that in the event of high nitrate leaching at low rainfall, a crucial determining factor could be rainfall timing relative to the soil nitrate concentration at percolation (Williams and Kissel, 1991). Considering the low maize biomass (Fig. 1) and N uptake (Table S4) obtained in the 2nd year, nitrate likely accumulated in the topsoil during the brief dry spells, exposing it to potential leaching in the event of high rainfall. The evidence was seen in the sharp increase in the soil water content at a depth of 80 cm on 17/04/2020 (Fig. 3). This resulted from a 23 mm rainfall on 15/04/2020 after nine days of relatively low or no rain.

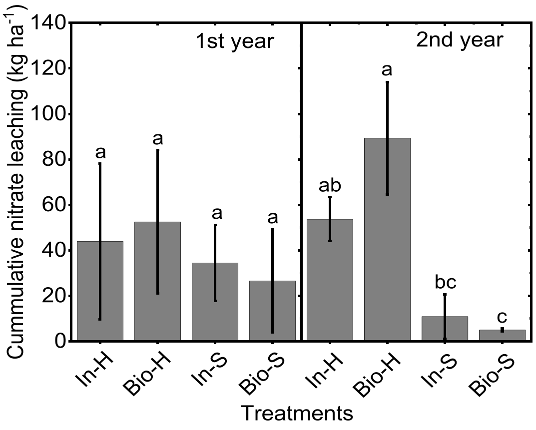

Fig. 2. Cumulative nitrate-N (kg ha^{-1}) leaching from biosolid versus inorganic fertilizer under humid and sub humid rainfall distribution. Significant difference was determined by Tukey test ($P < 0.05$). In = Inorganic fertilizer, Bio = Biosolid, S = Subhumid rainfall, H = Humid rainfall.

3.4. Relationship between rainfall and nitrate leaching

During the earlier sampling events in the 1st year, the nitrate concentration was below the actual detection limit (0.2 mg l^{-1}) for inorganic fertilizer treatment in the first sampling event (02/01/2019). The same was seen for the biosolid treatment in the first three sampling events (02, 13 and 29/01/2019) despite the high rainfall amount (58 mm) on 01/01/2019, with a resultant large volume of total percolate of >60 L per sampling event (Table not shown). High organic N (99%) in the applied biosolid may explain the delayed nitrate leaching from biosolid treatments. Dilution of nitrate concentration in the leachate could be one of the critical factors that led to low or no nitrate concentrations for all treatments during the first three sampling events before the relatively higher concentrations recorded on 08/02/2019 (Fig. 4A and B, 1st year). These phenomena are well explained by Huebsch et al. (2014), where dilution, mobilization and a combination of dilution and mobilization during one storm event or multiple rainfall events were suggested as critical scenarios in the presence or absence of nitrate in leachate. In the current study, however, constant monitoring of discharge to identify periods of dilution and mobilization was unattainable. Therefore, dilution was assumed for no detection in a relatively large volume (>50 L) of total discharge at sampling. Although Stueber and Criss (2005) observed low nitrate concentrations during storm events, it rapidly increased during heavy N fertilization, coinciding with one storm event. This finding corroborated the distinctly increased nitrate concentration observed in the 1st year for inorganic fertilizer treatments when three days of consecutive humid rainfall (total 39.5 mm) succeeded in the second split application on 22/02/2019 (Fig. 4A, 1st year).

It was evident during the 2nd year under humid rainfall (Fig. 4A, 2nd year) that inorganic fertilizer had less frequent percolation but a higher nitrate concentration per sampling event, while biosolids had more frequent percolation but lower nitrate concentrations, which accumulated to a higher amount over time. However, under sub-humid rainfall, biosolids produced relatively lower cumulative nitrate leaching under similar trends (Fig. 4C, 2nd year). The lower cumulative nitrate leached was attributed to the slower release of inorganic N from biosolids (Fig. S5), caused by lower rainfall in the 2nd year than in the 1st year. Higher nitrate leaching was expected as the crop reached physiological maturity (R5–R6) and N uptake was reduced (Bender et al., 2013). However, no percolation occurred at this stage (early to late April–May) as rainfall decreased (Fig. 4B and D, 1st and 2nd year).

On 15/02/2019, in the 1st year, the highest nitrate leaching occurred, which coincided with the V12 stage of growth (Fig. 4A and B, 1st year). At this stage, N uptake was relatively low, coupled with five days of consistent rainfall (11–15/02/2019) totalling 95.5 mm, leading

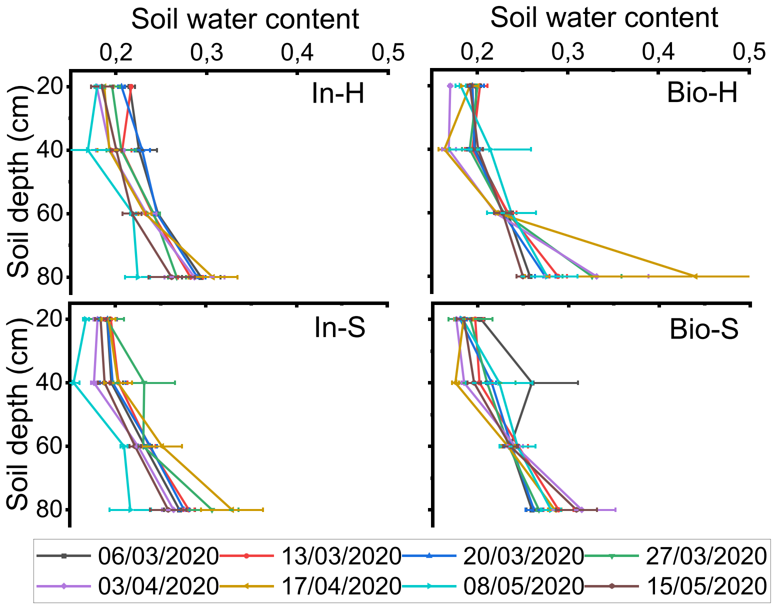

Fig. 3. Weekly/Biweekly soil water content during the second-year trial. In = Inorganic fertilizer, Bio = Biosolid, S = Subhumid rainfall, H = Humid rainfall.

to high nitrate leaching. In comparison to inorganic fertilizer, this nitrate concentration for biosolid was higher under humid conditions but lower under sub-humid rainfall. In the 2nd year, nitrate leaching peaked at V5 (02/03/2020) and VT (04/04/2020) for the biosolid and inorganic fertilizer treatments, respectively (Fig. 4A and B, 2nd year). At V5, N uptake was low, with relatively low rainfall. However, at VT, the N uptake was expected to be high, but rainfall increased. Under sub-humid rainfall conditions (Fig. 4C and D, 2nd year), the highest nitrate leaching occurred in the inorganic fertilizer treatment at V10, the peak of vegetative growth when the N uptake was relatively high. However, this coincided with heavy rainfall after a short dry spell.

3.5. *Relationship between nitrate leaching at early growth stage and maize yield*

The linear model for nitrate leaching at the early growth stage fitted to maize grain and biomass yields indicated good agreement (R^2 = 0.919–0.996) and significance. Stepwise regression revealed significant differences between treatments and years (Table S5), indicating the importance of nitrate leaching during the early growth stage in explaining the maize yield. The year × treatment interaction significantly affected nitrate leaching, accounting for 84% of the variation in maize biomass yield and 89% in maize grain yield. High negative coefficient values were also obtained between nitrate leaching and maize yield in all treatments (Table S5), indicating a strong relationship and potential to compromise maize yield with an increase in nitrate leaching.

In the first year, high rainfall in the early stages of maize growth resulted in lower cumulative nitrate leaching from biosolid compared to inorganic fertilizer treatments (Fig. 5a). Despite the below-average rainfall during the early growth stages in the second year, the cumulative leached nitrate was higher from biosolid than the inorganic fertilizer under humid rainfall (Fig. 5b). This, however, did not compromise maize yield (Fig. 1). Similar findings were made by Pampana et al. (2021), who found that oat grain yield was unaffected despite significantly higher nitrate leaching at early development stage compared to inorganic fertilizer.

3.6. *Residual soil nitrogen*

Residual soil nitrogen is a risk indicator for nitrate leaching in subsequent planting seasons. In the first year, residual soil total N (RSTN) followed the order Bio–S > Bio–H > In–H > In–S in the 1st year (Fig. S6A), and Bio-H > Bio–S=In–S=In–H in the 2nd year (Fig. S6B). It is generally assumed that approximately 30–40% of applied organic N is mineralized in the 1st year (Cogger et al., 2001; NRC, 1996; Reed et al., 1991). In this study, it was found that under sub-humid and humid rainfall, 28% and 30% (1st year) and 26% and 28% (2nd year) of the biosolid organic fraction were converted into inorganic forms, respectively (Fig. S5). Comparison between inorganic fertilizer and biosolid treatments showed that the 1st year RSTN from biosolids was 27% and 55% higher than inorganic fertilizer under humid and sub-humid rainfalls, respectively. In the 2nd year, however, RSTN was 68% higher in biosolids than in inorganic fertilizers under humid rainfall. In contrast, biosolids and inorganic fertilizer under sub-humid rainfall had similar values of RSTN.

Before the study, NO_3^- concentrations were below the lower limit for optimum maize growth (Blackmer et al., 1989) (Fig. 6a). The residual NO_3^- concentrations were generally lower than the initial values (Fig. 6b). Accumulation in the lower profile was barely existent. The Bio-H treatment had the highest NO_3^- concentration (2.4 mg kg^{-1}) at the topsoil. In comparison to the initial NH_4^+ concentrations at the topsoil (Fig. 6c), the residual NH_4^+ was lower under biosolid application but increased in the inorganic fertilizer treatments (Fig. 6d). These findings suggest that the high RSTN observed under the biosolid-humid rainfall treatment was mainly in the organic form. By this, considerable nitrate leaching is less likely to occur from biosolid application at the onset of rainfall before the next planting season. However, this may depend on the N mineralization (Badza et al., 2020).

4. Limitations of the study

The constraints of the current study were: First, the experiment was conducted in one agro-ecological zone (subhumid) while representing the rainfall of two agro-ecological zones by mimicking the humid rainfall through irrigation due to logistical and financial constraints. Thus, excluding temperature effects on N mineralization in the humid rainfall treatments was inevitable. Joshi et al. (2017) reported accelerated

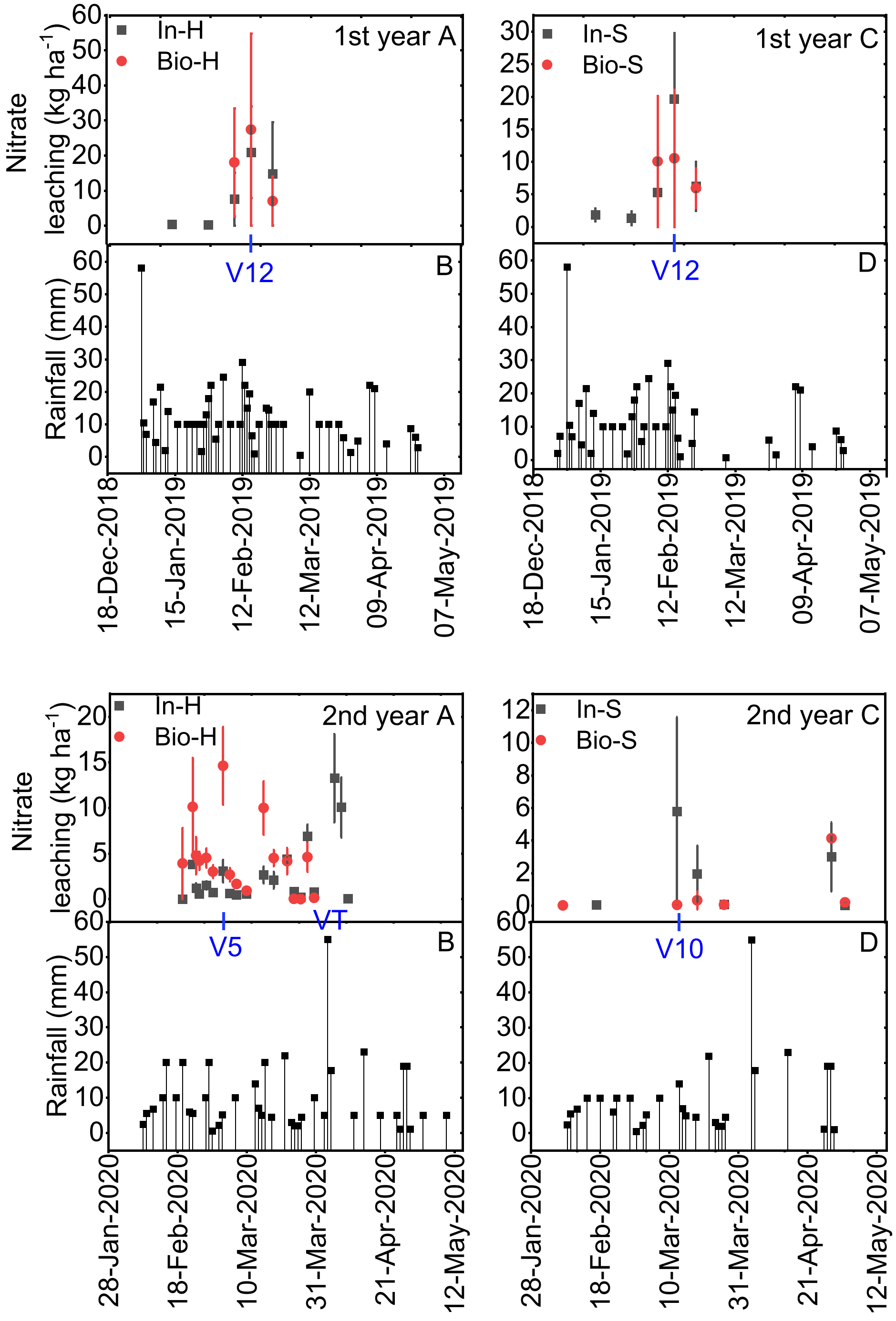

Fig. 4. Nitrate leaching responses to inorganic fertilizer and biosolid application under humid and sub-humid rainfall. In = Inorganic fertilizer, Bio = Biosolid, S = Subhumid rainfall, H = Humid rainfall.

nitrification at an ambient temperature shift of +3 °C. Thus, owing to considerable atmospheric temperature differences (≈4 °C) between the sub-humid and humid agro-ecological zones, rainfall effects alone may be inadequate for validating the SARA model crop-site-specific recommendations for humid regions. In contrast, field incubation studies in these agro-ecological zones conducted by Badza et al. (2020) indicated that despite the lower soil temperatures in the subhumid zone than in the humid area, net N mineralization was similar. The influence of other factors, such as inherent soil physicochemical properties, on the N mineralization rate (Ogbazghi et al., 2016) reinforces the need for a customized biosolid application strategy.

Second, the N leached during the fallow period between harvesting and the next planting season was unaccounted for, which may have resulted in an underestimation of N lost through leaching. However, this depends on the prevailing rainfall (Badza et al., 2020; Ogbazghi et al., 2016) and biosolid recalcitrant fraction to N ratio (Tesfamariam et al., 2015b).

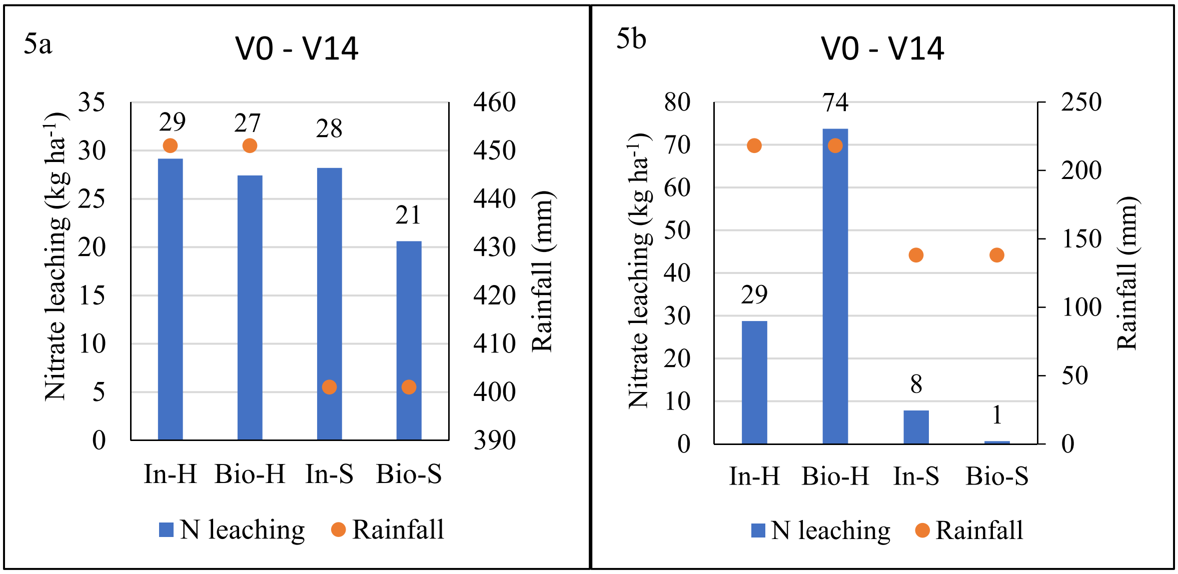

Fig. 5. Relationship between rainfall and nitrate leaching at early (V0–V14) growth stage of maize in, a. 1st year. b. 2nd year. In = Inorganic fertilizer, Bio = Biosolid, S = Subhumid rainfall, H = Humid rainfall.

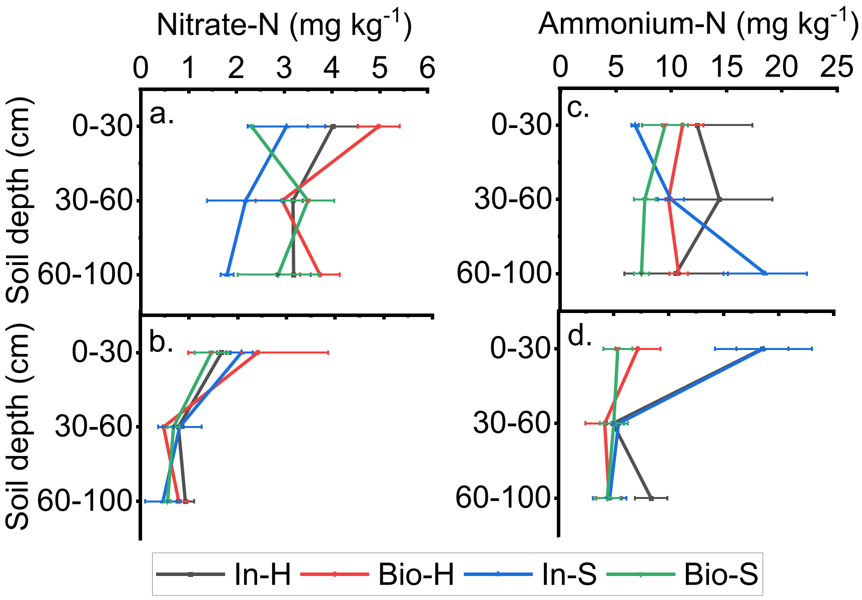

Fig. 6. (a) Soil nitrate-N with depth before first year treatments application. (b) Soil nitrate-N with depth at second year post-harvest. (c) Soil ammonium-N with depth before first year treatments application. d. Soil ammonium-N with depth at second year post-harvest. In = Inorganic fertilizer, Bio = Biosolid, S = Subhumid rainfall, H = Humid rainfall (coloured in print) (Note: single-column fitting image).

5. Conclusion

- This study demonstrated that rainfall variations impacted nitrate leaching, but the cumulative nitrate leaching for biosolid and inorganic fertilizer treatments were comparable.
- Maize yield under the humid rainfall was not compromised in the 2nd year, despite biosolid having more than twice as high nitrate leaching compared to inorganic fertilizer at the early (V0–V14) growth stage.
- The significantly lower grain yield from biosolid compared to inorganic fertilizer in the 2nd year under subhumid rainfall seemed to be due to the sub-optimal rainfall rather than nitrate leaching.
- The pattern in this study suggests that the concern of a compromise in maize yield due to higher nitrate leaching from biosolid at the early growth stage is largely unfounded.
- Given the high post-trial residual total N in the biosolid-amended soil under the humid rainfall and the potential temperature effects on N mineralization, it is suggested to ascertain the findings in the humid agro-ecological zone.

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Authorship declaration interests

Eyob Tesfamariam: Conceptualization, Methodology. Chioma Ogbenna: Methodology, Formal analysis, Writing - original draft. Eyob Tesfamariam: Writing - review & editing, Funding acquisition. Chioma Ogbenna: Writing - review & editing. Chioma Ogbenna: Performed the experiments. Eyob Tesfamariam: Resources, Supervision.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2023.100680.

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Glossary

SARA: Sludge Application Rate Advisory
USEPA: United States Environmental Protection Agency
SASRI: South African Sugarcane Research Institute
UNDP: United Nations Development Programme